

On the Universally Composable Security of OpenStack^{*†}

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Abstract

OpenStack is the prevalent open-source, non-proprietary package for managing cloud services and data centers. It is highly complex and consists of multiple inter-related components which are developed by separate, loosely coordinated groups. We initiate an effort to provide rigorous and holistic security analysis of OpenStack. Our analysis has the following key features:

1. It is *user-centric*: It stresses the security guarantees given to users of the system, in terms of privacy, correctness, and timeliness of the services.
2. It provides *defense in depth*: It considers the security of OpenStack even when some of the components are compromised. This departs from the traditional design approach of OpenStack, which assumes that all services are fully trusted.
3. It is *modular*: It formulates security properties for individual components and uses them to assert security properties of the overall system.

We base our modeling and security analysis in the universally composable (UC) security framework, which has been so far used mainly for analyzing security of cryptographic protocols. *Indeed, demonstrating how the UC framework can be used to argue about security-sensitive systems which are mostly non-cryptographic in nature is another main contribution of this work.*

Our analysis covers only a number of core components of OpenStack. Still, it uncovers some basic and important security trade offs in the design. It also naturally paves the way to a more comprehensive analysis of OpenStack.

Index terms— Modular Security Analysis, Universal Composability, Cloud Security, OpenStack

*The order of the authors is alphabetical among the first three authors, and again alphabetical among the remaining authors. Indeed, the first three authors contributed significantly more to the paper than the other ones.

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1 Introduction

Analyzing security properties of large-scale information systems is a daunting task. A first challenge, that is almost intractable in and of itself, is to adequately articulate and rigorously express the security requirements from the system in the first place. Indeed, adequately capturing even simple, intuitive concerns is non-trivial. Furthermore, security is often inseparable from the expected functionality, which is complex in of itself. It also invariably has multiple facets and competing requirements that need to be reconciled.

A second challenge is to rigorously assert the specified properties. This challenge is even more daunting, especially when the system consists of multiple components and one has to take into account inter-component interactions, potential failure of individual components, and the associated potential vulnerabilities.

The natural way to deal with such complexities is modularity: formulate and assert the security properties of individual components, and then deduce security properties of the overall, composite system from the security properties of the components, as well as those of the way in which the components are put together. This breaks down the overall analysis into multiple steps where each step deals with a much simpler system. Furthermore, when successful, the analysis would deduce the overall security of the system from the security of the components, and the security of the overall design given the components. Still, breaking down a system to components in a way that allows for effective composable *security* analysis is a non-trivial task in of itself.

A number of frameworks for modular security analysis for cryptographic protocols have been developed over the years, e.g. [1, 2, 3, 4, 5, 6, 7]. Furthermore, a number of works have made advancements to use these frameworks to analyze security of security-sensitive systems that are non-cryptographic in nature, e.g. [8, 9, 10, 11, 12]. Extending these cryptographic frameworks to handle systems with complex interfaces and sizeable codebase is a challenging endeavor — but one that holds great promise. In particular, it opens the door to rigorous, yet modular and approachable security analysis of large-scale software systems. Indeed, such analysis can be very valuable even in systems that use little or no cryptography.

In this work, we initiate modular security analysis of OpenStack, which is a large-scale distributed system with complex interfaces and use cases. It is also extremely security-sensitive. We perform our analysis within the Universally Composable (UC) security framework.

OpenStack OpenStack is a software package for data centers and virtualization services, including remote computation, storage, networking, and related services. It is open-source, and it is developed in a distributed and loosely coordinated way by multiple contributors across the globe. OpenStack is by far the most popular non-proprietary software package of its kind.

The OpenStack project began in 2010 as a collaboration between two groups: Rackspace, a public IaaS provider selling cloud services, and NASA, a part of the United States government that wanted to take advantage of the elasticity and datacenter efficiency benefits that come from combining different workloads into a single private cloud [13]. Since then, it has grown to be a large open source project with over 3.5 million lines of code, and over 6,000 contributors and hundreds of implementations around the world [14, 15]. There is a governance body [16] that actively manages the development and stability of OpenStack.

The design is inherently modular, with 23 modules where each module has some pre-specified functionality, as well as interfaces with the other modules it interacts with. It should be noted

though that the functionality of the interfaces is not completely pinned down; indeed some modules have multiple implementations that provide slightly different functionality. Also many of the modules allow for a variety of underlying software packages as plug-ins. Some of the main modules of OpenStack include:

Nova (compute): Manages the creation, maintenance and removal of virtual machines (VMs).

Glance (image repository): Stores and manages the images loaded to VMs.

Cinder & Swift (block & object storage): Manage the storage of data (in blocks, volumes, and more general objects) for VMs.

Neutron (networking): Provides internal and external virtual networks for VMs.

Keystone (access control and key management): Holds the permission information controlling the access of users to services and data. Interacts with users and all other modules to enforce the permission policies.

Horizon (user-side dashboard): Provides an interface between users of the system and its service modules.

Each one of these modules is a complex, distributed system in and of itself, sometimes with multiple subdivisions, plug-ins, and alternative implementations.

In terms of security guarantees and analysis, the OpenStack consortium offers an extensive and illuminating security guide [17]. However, this guide concentrates on security measures for protecting the OpenStack package itself from external intruders and attackers. Other literature on the security of OpenStack (e.g. [18, 19, 20, 21, 22, 23]) also concentrate on individual components and mitigation of specific attack vectors. However, to our knowledge we are the first to model and assert the overall security guarantees that the OpenStack services collectively provide to its users.

Furthermore, the design of OpenStack appears to implicitly assume that all components of an OpenStack-based service are trusted. In other words, there is no attempt to guarantee security (at any level) in case that any part of the entire package is compromised or not functioning properly. We discuss this point further below.

Our analysis We initiate a study of the security properties provided by OpenStack when viewed as a service to external users. This includes properties such as confidentiality and integrity of *data* (both in storage and in transition), confidentiality and correctness of *computations*, as well as timeliness and resource preservation. We also consider the extent to which these properties are preserved under various attack vectors and when various components of the system are compromised.

We base our analysis in the universally composable security (UC) framework [3], which provides a way to articulate security properties in a rigorous and precise way. Furthermore, the framework provides a natural and convenient mechanism for arguing about the preservation of security when programs and systems are composed in a modular way. Indeed, from this perspective the UC framework appears to be ideally suited to analyzing OpenStack whose design is inherently and predominantly modular.

On the other hand, the UC framework was initially created, and predominantly used, for analyzing cryptographic protocols. These are very different than OpenStack: while their analysis requires creative reductions to hard computational problems, they are vastly simpler in terms of

number of components, cases, and volume of code. Indeed, coming up with an effective modeling of OpenStack within the UC framework is a labor intensive, non-trivial line of research. This work makes the first step in this direction.

Recall that in the UC framework the security requirements from the analyzed system (or, service) π are analyzed jointly with the functionality requirements from the service. This is done by way of formulating an *ideal service* \mathcal{F} , which specifies the desired response (or lack thereof) to any potential external input. Roughly speaking, the service π is said to emulate the ideal service \mathcal{F} if no external environment can tell whether it is interacting with π or with \mathcal{F} .

In order to account for some level of allowable “slack” for π relative to \mathcal{F} , the framework allows the analyst to introduce an intermediary, or a *simulator* S that controls some of the interfaces between \mathcal{F} and the environment. That is, service π is now said to emulate an ideal service \mathcal{F} if there exists a simulator S such that no external environment can tell whether it is interacting with π or with a system where some of its APIs connect to \mathcal{F} , and other APIs connect to S . (Typically, S connects to APIs that we don’t consider to be part of the desired functionality, such as the communication between components of the implementing protocol.)

An attractive property of this definitional style is the following natural security-preserving composability: Since the specification \mathcal{F} is written as an “idealized” service in and of itself, one can design and analyze some other system (or, service) ρ where the components of ρ make calls to one or more instances of the service \mathcal{F} . The UC framework guarantees that the protocol $\rho^{\mathcal{F} \rightarrow \pi}$, where each instance of \mathcal{F} is replaced by an instance of π , continues to exhibit the same security and correctness properties as the original protocol ρ . In particular, if ρ emulates some other ideal service \mathcal{G} , then $\rho^{\mathcal{F} \rightarrow \pi}$ will emulate \mathcal{G} just the same. (Note that both π and ρ may well be distributed, multi-component systems in and of themselves.)

This work We provide initial modeling and analysis of the overall design and operation of OpenStack, as well as the functionality and security requirements from a number of core modules (essentially the modules described above with the exception of Swift and Neutron). Our analysis validates the overall security of the design, while at the same time exposing some (known) security weaknesses. We also propose and analyze methods for overcoming these weaknesses.

We stress that our analysis only covers the high level design of some main components of OpenStack. We defer to future work the modeling and analysis of additional components, as well as more detailed analysis of the structure and security of individual components.

We first formulate an ideal cloud \mathcal{F}_{Cloud} that provides a simple specification of the functionality and security that we assert OpenStack achieves. This formulation naturally involves many design choices and parameters that affect the security and functionality requirements imposed on the system. We discuss them within. One important aspect of our ideal cloud specification is the expected behavior upon various types of partial corruption (which correspond to corruption of individual modules in an OpenStack service). This is where we depart from the current OpenStack package, which does not provide any security guarantees as soon as any module is corrupted.

Next we formulate ideal functionalities that correspond to the four services we capture, namely $\mathcal{F}_{Compute}$, \mathcal{F}_{Image} , $\mathcal{F}_{BlockStorage}$, and $\mathcal{F}_{Identity}$. Our models for each OpenStack service aim at capturing the functionality and intricacies of the actual components of OpenStack, modulo some necessary modifications that are essential for security. Also here we face a number of choices that represent different levels of security of these services.

These services communicate with each other via secure message transmission \mathcal{F}_{SMT} . Addition-

ally, they use an external network \mathcal{F}_{ExtNet} to communicate with the user, or more specifically to connect to the user’s *Dashboard* program (which is our abstraction of Horizon). Collectively, the joint interactive effort of these services and protocols comprise a cloud of *OpenStack Services*. In the two main results of our paper (Theorems 2 and 3), we prove that the OpenStack services collectively UC-realize our ideal cloud.

Security weaknesses exposed As long as all the components of an OpenStack service continue to function properly, the Open Stack design indeed provides adequate security, namely secrecy and correctness of data and computations.

At the same time, our analysis formally exposes the extent to which OpenStack is vulnerable to the compromise to a subset of components. We remark that the case where some components become compromised is quite realistic; indeed, some components, such as the VM manager Nova, are more susceptible to attack just because they are exposed to a richer attack surface from malicious VMs. Consequently it is prudent to design the system so as to minimize the damage from the compromise of individual components, and to perform analysis that provides some security guarantees even in case that some components are adversarially controlled.

The main source for this vulnerability is OpenStack’s *bearer token* mechanism to authenticate users and verify their authorization to access resources. Bearer tokens operate as follows. When user U wishes to launch a VM, it first contacts the identity service Keystone, and obtains a token that represents for Keystone the user U and its capabilities. U then hands the token to the compute service Nova, which starts a VM for U with the desired parameters, and then *continues to use the token on behalf of U* in order to obtain additional services for U ’s VM (or VMs) as becomes necessary. For instance, Nova may use the token on behalf of U to obtain storage or networking services for the VM. (A natural alternative to the token mechanism is a digital signature by Keystone regarding the capabilities of U . However, this solution has been rejected by the OpenStack community due to its computational and bandwidth overhead.)

As long as the communication between services is secured via point-to-point secure session protocols (say, via TLS), this mechanism provides security against external attackers that only control the network. However, this mechanism allows a corrupted component (say, Nova) to impersonate tokens on behalf of any user. When the inter-process communication is not secured in a point-to-point way, we have that *any* rogue OpenStack entity that can eavesdrop to the inter-service communication (say, a hypervisor that was compromised by its tenant VM) can potentially have access to all current bearer tokens in the system. Indeed, previous works (e.g. [24]) have already pointed out this weakness and proposed limiting the scope of these bearer tokens by setting expiration times and other scoping mechanisms.¹

It should be stressed that, upon each new use of the token, each new service verifies the token again with Keystone. Ergo, tokens that are invalid will not cause damage. However, when the tokens are broadly scoped, nothing prevents a rogue component from using legitimate tokens of existing unsuspecting users to compromise both the integrity and the secrecy of their data.

This work analyses OpenStack with two token mechanisms. First, we analyze OpenStack’s existing bearer tokens. Our analysis shows that the current OpenStack realizes an “ideal cloud” specification that provides little security as soon as any component is corrupted.

¹For simplicity of exposition we leave the timeout mechanism (as well as measurement of real time) outside the model. We note that timing mechanisms can be added in a relatively straightforward way, using the UC-style modeling of network time of Canetti et al. [25]. Indeed, the ability to modularly add the consideration of time is another demonstration of the power of composable security analysis.

We then construct a new, stronger *one-time* token mechanism that is a more stringent variant of the mechanism proposed in [24], and we prove that this mechanism suffices for realizing an ideal cloud that provides some meaningful security properties even when some of the services are fully corrupted. In a nutshell, our mechanism has Keystone generate a token that is authenticated via a cryptographic authentication tag, using Keystone’s own master secret key. A token-specific key is then derived and sent to the user’s Horizon module over a secure communication channel. The user then scopes the token for a *single use* by a specific set of services (e.g., starts a specific VM with a specific image and a specific amount of block storage attached), authenticates the scoped token with the derived key it received from Keystone, and sends the derived token to the appropriate service (say, Nova). Nova then contacts Keystone to verify the token before honoring it. In addition, Nova passes the token to other services as needed (say, Glance or Cinder); this is done over authenticated channels. Each service *records the source of the token*, and it interacts with Keystone to verify the token *along with the service from which the token arrived*.

We show that the additional security provided by the limitation to one-time use, together with the ability to identify the entity that provides the token, suffices for realizing a significantly stronger variant of the ideal cloud specification that limits the damage caused by corrupted services. Allowing the Horizon module to scope the token enables the fine-grained scoping of the one-time token. Furthermore, the Horizon module of a user is now capable of generating multiple one-time tokens on its own, without intervention of Keystone.

Another issue is the level of compartmentalization around VMs and hypervisors. Our basic modeling represents a VM as a new process that runs independently of the core Nova component and all other VMs. This means that a VM continues to execute unmodified *even when Nova is corrupted*. This is a strong guarantee, which the current OpenStack package does not meet (for instance, a hypervisor that’s corrupted by its tenant VM has access to all the communication between components on the main communication bus). To capture the properties of the existing design we formulate an additional corruption mechanism whereby the ideal cloud no longer provides any secrecy or integrity guarantees as soon as any component is corrupted. (Still, this modeling makes it possible to assert stronger security properties for VMs, when employing appropriate mechanisms, such as homomorphic encryption or other cryptographic protection mechanisms.)

Towards mechanized analysis An important aspect of this work, that sets it apart from many previous works in the UC framework, is that we provide in full detail the specifications of the ideal cloud and the individual services, as well as the descriptions of the simulators and the proofs of security, without glossing over steps. As a consequence, our proofs and specifications are decently long and tedious. Indeed, while for this paper we stick to pen-and-paper proofs, we believe that our modeling and analysis are readily amenable to mechanization, and also to some level of automation. Natural candidates for tools that would enable such mechanized analysis include the EasyCrypt tool [26], the FCF tool [27], or the CryptHOL tool [28]. We leave such mechanization to future work.

1.1 Related Work

Security Analysis of Clouds The OpenStack Security Guide [17] goes into depth about the security of different aspects of configuring the many different pieces of OpenStack. However, it does not provide any security analysis, formal or otherwise, nor does it consider situations where a cloud service is compromised.

Other works have focused on the compromise of compute nodes [29] or parts of the management infrastructure [30], and Sun et al. [31, 32, 33] specifically discuss limiting the scope of compromised OpenStack services. These works conclude that corrupted cloud components have far-reaching security impact and can in many cases compromise the privacy and integrity of all cloud operations. Their conclusions highlight the need for a formal security analysis of service corruptions in OpenStack, which we provide with our construction. Sze et al. [29] additionally propose an alternative authorization tokening mechanism to reduce the effect of corrupted compute nodes, but their construction neither protects against compromise of other services nor provides token authentication and replay prevention. We have focused on addressing these requirements as well as shifting control of token generation and scope to the user responsible for the request. Also, crucially, we provide a security analysis that concretely specifies the security gain.

Using UC Canetti et al. [34] show how the UC framework can be used to analyze the simple components of a file system in isolation and to guarantee that these components maintain their behavior in the larger system even under adversarial conditions. This demonstrates basic integrity properties of the file system, i.e., the binding of files to filenames and writing capabilities. Gajek et al. [35] evaluate in the UC framework the emulation of secure communication sessions by the composition of key exchange functionalities that are realized by the TLS handshake and record layer protocols. Canetti et al. [36] give a modular and global universally composable analytical framework for PKI-based message authentication and key exchange protocols.

For our analysis, we apply the style of [34] to the larger and more complex OpenStack framework and utilize aspects of [35, 36] to achieve secure communication. We further use our construction to demonstrate security flaws in OpenStack’s current authorization mechanism and assess the improvements provided by our suggested changes.

Alternative Formalisms The UC framework is not the only option for formal analysis of computing systems. In particular, Gu et al. [10] use the Coq proof assistant to analyze and provide an abstraction of layers of the computing stack including the kernel, networking, etc. They developed and verified a certified kernel with 37 of these abstraction layers.

We chose to use UC for our analysis because its modularity and composability aligned well with the structure of OpenStack which is itself composed of many services that interact via a series of well defined APIs. These services support varying interchangeable implementations that would be difficult to support using a less modular proof framework.

1.2 Organization

The remainder of this work is organized as follows. We begin in Section 2 by providing some background on OpenStack along with an overview of the UC framework. Next, Section 3 provides an informal account of our modeling of OpenStack services and the security properties we chose to model. We use an example workflow to highlight the modularity of our design. In Section 4, we fully specify the functionalities for the OpenStack services and an idealized monolithic cloud, and then we prove that the former UC-realizes the latter. Then, we present a stronger token mechanism in Section 5, and we perform another UC analysis in Section 6 to prove that our new tokens improve the security of OpenStack in the event that some services are compromised. Finally, we conclude with a discussion of future work in Section 7.

2 Background

In the following subsections, we focus on surveying OpenStack and briefing UC.

2.1 OpenStack

As outlined in the Introduction, OpenStack is a modular, distributed, open-source cloud computing software stack for providing Infrastructure as a Service (IaaS) to multiple (potentially untrusting) users. In this section, we describe OpenStack’s operation with a focus on some of the security concerns of its authorization system.

Modular services OpenStack comprises several distinct *services* that offer different features like Virtual Machine (VM) computation, object storage, identity authentication and authorization, block data storage, networking, and VM image management. Many services act primarily as orchestration engines, exposing the functionality of a rich ecosystem of plugins through the service APIs [37]. For example, the VM service (called Nova) has plugins supporting different hypervisors, including Microsoft HyperV, Xen and VMware. Services are independent, differing both in development, where services have separate teams, and in deployment by *cloud providers*, where services can be managed and scaled separately.

OpenStack’s identity service, named Keystone, links these independent services by serving as a common method for authenticating and authorizing users to the different services. Keystone codifies permissions for users based upon the *projects* they may access and the *roles* they have on these projects. A project is simply a collection of resources (VMs, networks, object storage, etc) that a group of authorized users may access. Roles describe the actions a user may take within each project. While OpenStack supports a robust set of roles, in practice most deployments only configure two: an ordinary *member* and an *administrator* with additional power.

Tokens To determine a user’s project and role, Keystone gives the user a *bearer token* after authenticating with their credentials (e.g., username and password); users include this token in API requests to other services for authentication and authorization. Services pass this token to Keystone, which returns back a *(project,role)* tuple if the token was valid. Services then make all authorization decisions based on that tuple. Bearer tokens are used similarly in other popular protocols, like OAuth [38]. Because possession of a bearer tokens grants access to resources, care must be taken to protect them from unauthorized parties using methods like TLS [17].

Service interactions on behalf of an end user allow for more complicated tasks such as attaching storage volumes to a compute node. The compute service is able to send a user’s token to the storage service which can in turn verify with the identity service that this token has access to the requested volume and attach it to a node without needing to check with the end user itself.

OpenStack uses plugins to Keystone to implement tokens, the most popular being UUID and Fernet [39]. UUID tokens issue random, universally unique identifiers [40] to users after a successful first authentication with Keystone, and stores them in a database with other required information such as expiration time, the project and role associated with it.

The Fernet token is a recent innovation that uses cryptography to provide authenticity without accessing a central DB. It is a mechanism by which keystone creates a private, authenticated channel to itself. It has quickly become the preferred token format for OpenStack as they do not require maintaining a central database of valid tokens, which adds network load and latency.

Trust model Many of OpenStack’s design choices and security issues stem from its broad trust model, which assumes that all services act as faithful user agents. Providing security even in the case where some services are compromised does not appear to be a design goal. Furthermore, interactions between services in OpenStack are optimized in light of this trust. However, OpenStack’s unprotected interior means that a (partially) compromised service can do a great deal of harm: acquiring a single bearer token allows the compromised service to impersonate the user for any subsequent action.

2.2 Universally Composable Security

Here, we provide a brief overview of the UC framework. See [3] and [41] for more details. (This overview is taken almost verbatim from [36].)

We focus on the notion of protocol *emulation*, wherein the objective of a protocol π is to imitate another protocol ϕ . In this work, the entities and protocols we consider are polynomial-time bounded Interactive Turing Machines (ITMs), in the sense detailed in [3].

2.2.1 Systems of ITMs

To capture the mechanics of computation and communication among entities, the UC framework employs an extension of the ITM model. A computer program (such as for a protocol, or perhaps program of the adversary) is modeled in the form of an ITM. An execution experiment consists of a system of ITMs which are instantiated and executed, with multiple instances possibly sharing the same ITM code. A particular executing ITM instance running in the network is referred to as an ITI. Individual ITIs are parameterized by the program code of the ITM they instantiate, a party ID (pid) and a session ID (sid). We require that each ITI can be uniquely identified by the identity pair $\text{id} = (\text{pid}, \text{sid})$, irrespective of the code it may be running. All ITIs running with the same code and session ID are said to be a part of the same protocol session, and the party IDs are used to distinguish among the various ITIs participating in a particular protocol session.

2.2.2 The Basic UC Framework

At a very high level, the intuition behind security in the basic UC framework is that any adversary \mathcal{A} attacking a protocol π should learn no more information than could have been obtained via the use of a simulator S attacking protocol ϕ . Furthermore, we would like this guarantee to hold even if ϕ were to be used as a subroutine in arbitrary other protocols that may be running concurrently in the networked environment and after we substitute π for ϕ in all the instances where it is invoked. This requirement is captured by a challenge to distinguish between actual attacks on protocol ϕ and simulated attacks on protocol π . In the model, attacks are executed by an environment E (Env) that also controls the inputs and outputs to the parties running the challenge protocol. E is *constrained* to execute only a single instance of the challenge protocol. In addition, it is allowed to interact freely with the attacker (without knowing whether it is \mathcal{A} or E). At the end of the experiment, the environment is tasked with distinguishing between adversarial attacks perpetrated by \mathcal{A} on the challenge protocol π , and attack simulations conducted by S with protocol ϕ acting as the challenge protocol instead. If no environment can successfully distinguish these two possible

scenarios, then protocol π is said to *UC-emulate* the protocol ϕ . We state the formal definition:²

Definition 1 (UC-emulation). *Let π and ϕ be multi-party protocols. We say that π UC-emulates ϕ if for any adversary \mathcal{A} there exists a simulator S such that for any environment E , we have:*

$$\text{EXEC}_{\pi, \mathcal{A}, E} \approx \text{EXEC}_{\phi, S, E}$$

Defining protocol execution this way is sufficient to capture the entire range of network activity that is observable by the challenge protocol but may be under adversarial control.

2.2.3 Universal composition

the UC framework admits a very strong composition theorem, which guarantees that arbitrary instances of ϕ that may be running in the network can be safely substituted with any protocol π that UC-emulates it. For simplicity, we first restrict attention to a special class of protocols, called subroutine-respecting protocols. Essentially, these are protocols that preserve a "hierarchical" structure of subroutine calls.

Definition 2 (Subroutine-respecting protocols). *We say that a protocol π is subroutine-respecting if the following properties hold with respect to every instance of π in any execution of any protocol ρ that makes subroutine calls to π :*

1. *No ITI which is a subsidiary of this instance passes inputs or outputs to an ITI which is not a party or subsidiary of this instance.*
2. *At first activation, each ITI that is currently a subsidiary of this instance, or will ever become one, sends a special message to the adversary, notifying it of its own code and identity, as well as the code π and session ID of this instance. We call this requirement subroutine publicness.*

Theorem 1 (UC-Composition). *Let ρ, π and ϕ be protocols such that ρ makes subroutine calls to ϕ . If π UC-emulates ϕ and both π and ϕ are subroutine-respecting, then protocol $\rho^{\phi \Rightarrow \pi}$ UC-emulates protocol ρ .*

Here $\rho^{\phi \Rightarrow \pi}$ denotes the composed protocol, i.e. protocol ρ where each call to an instance of ϕ is replaced by a call to an instance of π with the same session ID.

2.2.4 The Generalized UC Framework.

As mentioned above, the environment E in the basic UC experiment is unable to invoke protocols that share state in any way with the challenge protocol. In many scenarios, the challenge protocol produces information that is shared by other network protocol sessions. For example, protocols may share information via a global setup such as a public Common Reference String (CRS) or a standard Public Key Infrastructure (PKI). The basic UC framework discussed above does not address this kind of shared state; moreover, the UC composition theorem does not hold for non-subroutine-respecting protocols (i.e., protocols that share state information with other protocol sessions). Still, we would like to analyze such protocols in a modular way. To overcome this limitation, [41] proposes

²We consider only polynomial-time environments and adversaries. We omit from this overview the precise definitions of polytime and balanced environments, as they are inconsequential for this work.

the Generalized UC (GUC) framework. The GUC challenge experiment is similar to the basic UC experiment, only with an *unconstrained* environment. In particular, now E is allowed to invoke and interact with arbitrary protocols, and even multiple sessions of the challenge protocol. Some of the protocol sessions invoked by E may even share state information with challenge protocol sessions, and indeed, those protocol sessions might provide E with information related to the challenge protocol instances that it would have been unable to obtain otherwise. To distinguish this from the basic UC experiment, we denote the output of an unconstrained environment E , running with an adversary \mathcal{A} and a challenge protocol π in the GUC protocol execution experiment, by $\text{GEXEC}_{\pi,\mathcal{A},E}$. GUC emulation is defined analogously to the definition of basic UC emulation outlined above:

Definition 3 (GUC-emulation). *Let π and ϕ be multi-party protocols. We say that π GUC-emulates ϕ if for any adversary \mathcal{A} there exists an adversary \mathcal{S} such that for any (unconstrained) environment E , we have:*

$$\text{GEXEC}_{\pi,\mathcal{A},E} \approx \text{GEXEC}_{\phi,\mathcal{S},E}.$$

3 Modeling the Security of OpenStack: Informal Overview

In this section, we provide an informal account of our modeling of OpenStack and the security guarantees we assert. We first describe the behavior of each service and the risk associated with its compromise (Section 3.1). Then, we generalize from the service-level issues to provide informal, holistic security properties about OpenStack as a whole (Section 3.2). Next, we survey the design decisions and degrees of freedom that influence our model (Section 3.3). The informal account in this section is then followed by the actual definitions of the ideal cloud (Section 3.4) and the OpenStack services (Section 3.5).

Following the approach of the UC framework, we consider an adversarial environment E that controls all the interfaces of the legitimate users with the analyzed service, and in addition controls the communication network and the compromised components of the system.

In the context of our OpenStack service, this means that E can create new compute nodes with specific images of its choice, and link nodes to storage volumes subject to their capabilities. In addition, E can delay or drop arbitrary traffic on the external network (e.g., the Internet) over which users communicate with OpenStack. Next, E can compromise one or more OpenStack services, and thus we reinforce the services to provide defense-in-depth against service-level compromise. We consider both passive corruptions in which the compromised services continue to function normally but only leak their internal states to E , and complete corruptions where the compromised services start running code provided by E .

It is stressed that, while the modeling and analysis considers only the interaction between E and a single instance of our cloud service, the universal composition theorem guarantees that the same security guarantees continue to hold even when E is interacting concurrently with other instances of our system and with arbitrary other systems.

3.1 Functionality and Security of Each Service

We begin by describing several functionalities that encapsulate both the functionality and security relationships between the OpenStack services and the user’s dashboard protocol. In particular, we model the following functionalities in this work:

Dashboard Unlike the services described below, the Dashboard protocol is owned and operated by a single user. The Dashboard specifies the sequence of service requests needed to satisfy the user’s desires.

Compromising either the Dashboard or the user directly gives E the user’s credentials. Hence, E can execute any operation that the user has privileges to perform, but cannot otherwise tamper with the services in any way; in particular, users never learn each other’s credentials.

Identity $\mathcal{F}_{Identity}$ is responsible for managing credentials. It communicates with all users and services. We presume that $\mathcal{F}_{Identity}$ is instantiated with credentials for each user and service; in practice, these credentials correspond to bearer tokens that can be acquired via an authentication protocol involving a username/password. Subsequently, when any service $\mathcal{F}_{Service}$ receives a request, it may ask $\mathcal{F}_{Identity}$ to validate whether the request is authorized based upon the credentials provided. Additionally, note that while OpenStack uses a project/role based permissions system, our modeling is agnostic to the design of credentials.

When E compromises $\mathcal{F}_{Identity}$ essentially has full control of OpenStack. It immediately acquires the credentials of all users and can even change the permissions associated with them. Furthermore, because all services outsource their authorization decisions to $\mathcal{F}_{Identity}$, E can make any request and convince all services to execute it.

Compute $\mathcal{F}_{Compute}$ is responsible for managing the computing nodes on the cloud. It expects that the commands it receives over the network originate with the user’s dashboard service. Then, it relies upon the other OpenStack services to aid in fulfilling these requests. In more detail, $\mathcal{F}_{Compute}$ accepts commands from users to create, access, or delete computing nodes. In response, it may request images from \mathcal{F}_{Image} , connect to volumes stored on $\mathcal{F}_{BlockStorage}$.

Compromising $\mathcal{F}_{Compute}$ gives the environment extensive power: it may create or delete arbitrary nodes from $\mathcal{F}_{Compute}$ ’s records and may also capture the credentials of any user who subsequently accesses the service and use these credentials to falsify requests to other services. However, nodes already in existence enjoy a type of forward secrecy and integrity guarantee: once spawned honestly, they run independently of $\mathcal{F}_{Compute}$ and thus are not affected by its future corruption.

Image \mathcal{F}_{Image} stores virtual machine images that can be used when instantiating new nodes. These images may either be publicly accessible, or restricted only to users in the appropriate project. It only provides one method that $\mathcal{F}_{Compute}$ may invoke to request an image. \mathcal{F}_{Image} will respond as long as credentials with appropriate permissions are provided.

Compromising \mathcal{F}_{Image} allows the environment to learn both the images stored on the service as well as all user credentials that pass through it. However, a compromised \mathcal{F}_{Image} cannot directly influence other services since they never expect incoming connections directly from \mathcal{F}_{Image} .

Node \mathcal{F}_{Node} is our abstraction of a virtual machine; it can execute arbitrary programs on behalf of the project that owns it. Nodes are spawned by $\mathcal{F}_{Compute}$ but then act independently. Because $\mathcal{F}_{Compute}$ sends the code of a node over the network when it is instantiated, E may view all code executed within each node.

Compromising \mathcal{F}_{Node} gives the environment the ability to maul the computation performed within the node.

Storage and volumes $\mathcal{F}_{BlockStorage}$ manages the collection of data volumes available for use by users. It provisions volumes and attaches them to nodes, but then is out of the loop during subsequent data accesses.

Compromising $\mathcal{F}_{BlockStorage}$ permits the environment to attach and detach volumes from nodes of her choice. As a countermeasure to protect the data from unauthorized disclosure, the volume can be encrypted with a key that is only known to users with the correct project permissions.

Message bus OpenStack has an internal message queue to handle communication between services. We model the message bus using a secure message transmission functionality \mathcal{F}_{SMT} that protects the integrity of messages; additionally, it protects the confidentiality of tokens. This is a deviation from OpenStack as-is, which would allow any compromised service to breach message integrity and token confidentiality [21].

External communication between services and users (or their Dashboards) is handled instead by \mathcal{F}_{ExtNet} , which provides data confidentiality but does not authenticate the message’s sender. This modeling decision reflects the fact that OpenStack never verifies whether the user sending the message is actually the owner of the credentials contained therein.

3.2 Security Assertions

We list below several security guarantees. We stress that this is an informal description of forbidden or ‘blacklisted’ activities; the UC modeling of Sections 3.4 and 3.5 specifies exactly the set of permissible activities in a ‘whitelist’ format.

Authentication & authorization As long as $\mathcal{F}_{Identity}$ is uncompromised, E is limited to perform only those actions authorized by her projects and roles. Corrupt services can perform actions within their scope on behalf of the environment, but cannot influence uncorrupted services to perform unauthorized actions.

User control By moving away from bearer tokens, we can provide some user control even in the face of service-level compromises. Bearer tokens allow a corrupted service to impersonate a user to other, uncorrupted services and perform unintended actions. See Section 5 for details on our new tokening mechanism that removes the ability to replay user tokens and thus reduces the scope of a corrupted service to only those actions the service is able to perform directly. As \mathcal{F}_{Node} does not have access to user tokens, a corrupted \mathcal{F}_{Node} is unable to make changes affecting the OpenStack control or data plane. In this sense we model \mathcal{F}_{Node} as being fully isolated from other \mathcal{F}_{Node} instances or OpenStack services. Future expansion of our $\mathcal{F}_{Compute}$ model could include a hypervisor-like functionality detailing this isolation of \mathcal{F}_{Node} .

Resource control Users may restrict the environment from accessing and tampering with computing nodes, data volumes, and images as long as two services remain uncompromised: $\mathcal{F}_{Identity}$ and the service managing the object. Put simply, the services properly separate their control and data planes. For example, a corrupted compute can delete arbitrary user nodes, but it cannot influence the data stored on unattached volumes or the actions of other nodes (e.g., request a new image from the image service) without user authorization. This guarantee holds only if E does not legitimately hold the required project/role permissions.

Note that all of the guarantees described above only apply at the OpenStack layer. For instance: if you use OpenStack to spawn a web server with several known vulnerabilities and then connect it to the Internet, it is certainly possible for E to compromise your node. We make no guarantees about the safety of objects stored *within* OpenStack, only about their management *by* OpenStack.

Additionally, enforcing these security guarantees may come at the expense of flexibility. Having all security at the border and full trust within OpenStack makes it easier to realize the cloud vision of fungibility; for instance, if one node fails then any worker can be tasked automatically to take over for it. By chaining all authorization decisions back to the user, we reduce the cloud’s ability to self-regulate load balancing, scaling, and failover decisions.

3.3 Modeling Decisions

In this section, we discuss some of the decisions that impacted our modeling. First, we needed to decide the scope of $\mathcal{F}_{Compute}$ within Nova, the largest OpenStack service. At a high level, Nova comprises both the front-end API/scheduler and the back-end worker nodes. We choose to be more fine-grained so that our model is capable of describing the effects of compromising part, but not all of the (large) Nova codebase. This decision is made without loss of generality; compromising the entire Nova service corresponds in our mode to corrupting $\mathcal{F}_{Compute}$ and all \mathcal{F}_{Node} functionalities. Second, we augment $\mathcal{F}_{Identity}$ in Section 5 to strengthen tokens so they aren’t susceptible to data spills. Third, \mathcal{F}_{SMT} assumes that services register keys with the message queue so that it can enforce data integrity and token confidentiality in transit on the internal network.

3.4 The Ideal Cloud

Our ideal cloud functionality is a UC functionality that provides the user with the following set of commands:

CreateNode Allows a user to create a new node.

DeleteNode Allows a user to delete a node that they had previously created.

AccessNode Allows a user to execute a command on one of their nodes.

AttachVolume Allows a user to attach one of their volumes to an existing node.

DetachVolume Allows a user to detach a volume that had been attached to one of their nodes.

It is, in a sense, the simplest specification that is faithful in both functionality and security to the real services. As with all UC functionalities, the simplicity of the ideal cloud is intended to promote understanding and transparency of OpenStack’s behavior.

Here, we exemplify a simplified version of ideal cloud functionality \mathcal{F}_{Cloud} for the Delete Node function in Algorithm 1. (The full version of this algorithm, which includes message buffering, is written in Algorithm 8.) Our formulation of \mathcal{F}_{Cloud} is simple: \mathcal{F}_{Cloud} asks the permission of the simulator S for receiving every Delete Node request, and also its permission for sending each

Algorithm 1 Simplified Ideal Cloud (full version in Algorithm 8)

1: Upon receiving (Receiver, "Delete Node", session-id, node-id) from E : ▷ Step 1
2: Send-Sim (Receiver, "Delete Node", session-id, user-id, node-id); ▷ Step 2
3:
4: Upon receiving ("Confirm", session-id) from Sim: ▷ Step 3
5: **if** FindBuffer(Receiver, "Delete Node", session-id, user-id, node-id) **then**
6: **if** user-id is valid & user-id is allowed to delete node node-id **then**
7: Valid=1;
8: **else**
9: Valid=0;
10: **end if**
11: Send-Sim (Receiver, "Delete Node", session-id, user-id, node-id, Valid); ▷ Step 4
12: **end if**
13: Upon receiving ("Delete Node", session-id, Continue) from S : ▷ Step 5
14: NodeExist = 0;
15: **if** there is node with id=node-id & Valid=1 **then**
16: NodeExist = 1;
17: Delete node-id from the Node list;
18: **end if**
19: Send-Sim ("Delete Node Completed", session-id, Valid, NodeExist); ▷ Step 6
20:
21: Upon receiving ("Output Delete Node", session-id) from S : ▷ Step 7
22: **if** NodeExist=0 or Valid=0 **then**
23: Output("Delete Node", session-id, node-id, Fail) to E ; ▷ Step 8
24: **else**
25: Output("Delete Node", session-id, node-id, Success) to E ; ▷ Step 8
26: **end if**

notification back to the environment. Also, \mathcal{F}_{Cloud} does not hide the user credential validity information and the node existence information, as the adversary may discover the information from the execution of requests.

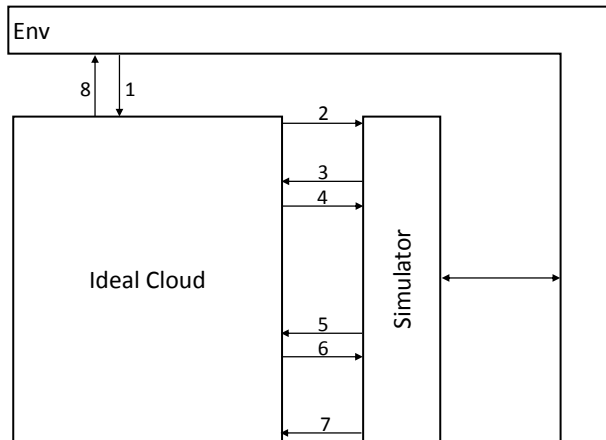


Figure 1: Delete Node in Ideal Cloud with the Simulator.

The information sent from the ideal cloud to the ideal-model adversary (i.e., to the simulator) represents the information that’s allowed to be leaked. Specifically, we hide the user and service credentials from the adversary, but leak all other information. We show that, even with this advantage, the ideal cloud guarantees that the adversary cannot impersonate a user and make requests on their behalf without compromising the user or services.

The ideal cloud also captures the security guarantees that are still provided in case some of the services get corrupted. In particular, the ideal cloud specifies the allowed degradation in security when a particular service is corrupted. (Notice that in the context of the ideal cloud the various services are merely names, or tags for the corruption operation made by the adversary.)

3.4.1 Ideal Cloud Walkthrough

In the ideal cloud setting, since we model the cloud as a single entity, there is no internal communication and it is left to the simulator to provide the necessary interaction with the environment. The DeleteNode request begins at Step 1 (Figure 1) when the environment sends a Delete Node message to the ideal cloud, through a dummy user who simply forwards inputs. The ideal cloud, could simply, check that the indicated user had the correct permissions to delete the requested node and, if so, removes it from the list of active nodes. However, to capture the fact that the system leaks whether a node was deleted, the ideal cloud notifies the simulator when a node is deleted. When the cloud receives the confirmation message from S in Step 3 it verifies that the node exists and that user has permission to delete it and relays this information to the simulator in Step 4. In Step 5, the simulator tells the cloud to continue. The cloud will then remove the node from the list of active nodes and notifies S in step 6. By receiving the continue message from S (step 7), the cloud outputs the success message to the environment through the dummy user in Step 8.

The simulator acts somewhat differently if a service (say, the Nova compute service) has been

compromised. For this reason, the ideal cloud sends S a list of user-ids that have been compromised when compute is corrupted. Additionally, we observe that the environment can send any message on behalf of the corrupted compute; since the simulator cannot directly answer any requests that the environment might make to another (uncompromised) service, S must forward such requests to the ideal cloud and get a response through its specific interface. This decreases the security guarantees that are provided by the cloud.

3.5 OpenStack Services

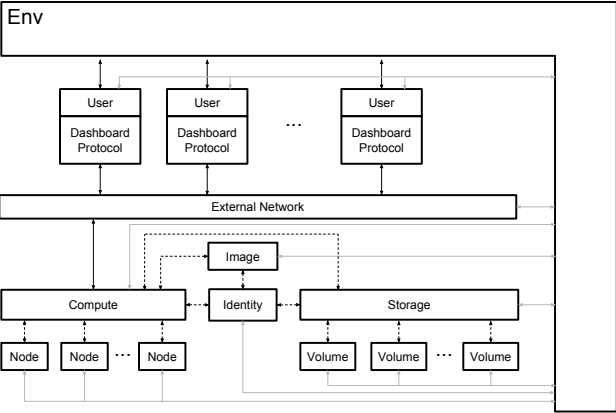


Figure 2: OpenStack Services: Arrows indicated expected lines of communication; other communication flow is possible, but will be ignored. Gray arrows show communication with the adversary, dashed black arrows indicate communication through \mathcal{F}_{SMT} , and solid black arrows indicate a direct communication.

In this section we describe our model of a simplified OpenStack cloud. The service functionalities, in conjunction with the message passing functionalities, collectively provide the same set of possible commands as the ideal cloud in the previous section.

We require both that the services maintain the confidentiality of users’ credentials while executing the commands and enforce that only a user in possession of the required credentials will be able to execute a command.

3.5.1 Example Workflow

We will walk through an example of how a user would delete their node using these service functionalities and a dashboard protocol. This example will show the interaction between the $\mathcal{F}_{Compute}$ and $\mathcal{F}_{Identity}$ services and the user. We note that all messages between services will pass through \mathcal{F}_{SMT} while any messages between the user and services will go through \mathcal{F}_{ExtNet} . We will briefly mention this during the description and it can be seen in Figure 3 as well.

This interaction begins at Step 1 (Figure 3, Algorithm 2) when the environment sends a DeleteNode message of the form (“Delete Node”, session-id, node-id) to the user. The user will then reformat this message in Step 2 to include their credentials and send it to \mathcal{F}_{ExtNet} to be forwarded to $\mathcal{F}_{Compute}$. When \mathcal{F}_{ExtNet} (Algorithm 3) receives the message it removes the user’s credentials and leaks the rest of the message to the adversary in Step 3. After receiving a (Confirm, session-id)

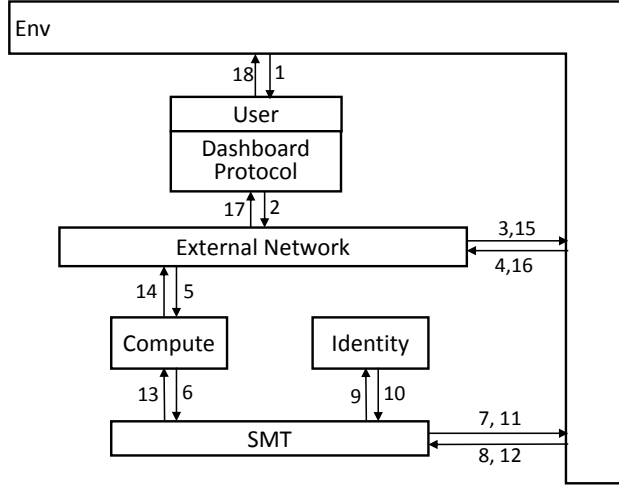


Figure 3: The Delete node functionality starts when the environment sends a "DeleteNode" message to the user. Next the user adds its credentials and sends it to the $\mathcal{F}_{Compute}$. Then, $\mathcal{F}_{Compute}$ creates a validation request to $\mathcal{F}_{Identity}$ in order to validate user's credentials. Based on the validation result and the node existence, $\mathcal{F}_{Compute}$ deletes the node and notifies the user. We describe the workflow in detail in Section 3.5.1.

message from the adversary in Step 4, \mathcal{F}_{ExtNet} sends the original message on to $\mathcal{F}_{Compute}$. In Step 5, (Algorithm 4) $\mathcal{F}_{Compute}$ receives the message from the user and creates a request of the form ($\mathcal{F}_{Identity}$, "Service Validation", session-id, $creds_{compute}$, $creds$, "Delete node-id ") to $\mathcal{F}_{Identity}$ via \mathcal{F}_{SMT} in Step 6 (Algorithm 5). The message passing by \mathcal{F}_{SMT} will proceed as in Steps 3-4. After $\mathcal{F}_{Identity}$ receives the validation message from $\mathcal{F}_{Compute}$ in Step 9 (Algorithm 6) it will check that the user has permission to delete the requested node and send an appropriate response to $\mathcal{F}_{Compute}$, again via \mathcal{F}_{SMT} , in Step 10. Once $\mathcal{F}_{Compute}$ receives the validation message from $\mathcal{F}_{Identity}$ in Step 13, it will delete the requested node if the node exists and the validation was successful, otherwise it will note that the request failed. In Step 14, $\mathcal{F}_{Compute}$ will send a message to the user, proceeding as before through \mathcal{F}_{ExtNet} , notifying them of the result of their request — either the successful deletion of the node or its failure. The user, upon receiving this message in Step 17 will output the result to the environment in the final step.

3.5.2 Realization of This Workflow

We write specifications for our functionalities in pseudocode with relevant snippets for the DeleteNode workflow shown in Algorithms 2, 3, 4, 5, and 6.

We allow the adversary to compromise users or services (Algorithms 7 shows corrupted Compute). A compromised user or service will reveal all of its internal state to the adversary and will from that point on be under full adversarial control. In particular, compromised users and services will not necessarily follow any specified protocol and can form their own messages at will. This is particularly relevant in our case because, upon compromising a service the adversary will learn not only its credentials, which are part of the internal state of the service, but also any credentials that service learns in the future. That is, any user that makes a request to a compromised service will also leak its own credentials to the adversary.

Algorithm 2 Dashboard Example Workflow (full version in Algorithm 9)

- 1: Upon receiving Request-Message from E :
 - 2: User U Creates ($U_{Dashboard}$, $\mathcal{F}_{Service}$, Request-Message, $creds$);
 - 3: Send- $\mathcal{F}_{ExtNet}(U_{Dashboard}, \mathcal{F}_{Service}, \text{Request-Message}, creds)$; ▷ Step 2
 - 4:
 - 5: Upon receiving (Sender, Output-Message) from \mathcal{F}_{ExtNet} : ▷ Step 17
 - 6: Output (Output-Message) to E ; ▷ Step 18
-

Algorithm 3 External Network Example Workflow (full version in Algorithm 10)

- 1: Upon receiving (Sender, Receiver, Message): ▷ Step 2
 - 2: Create New-Message by removing the credentials and replacing them by their IDs;
 - 3: Send-Adversary(Sender, Receiver, New-Message); ▷ Step 3
 - 4:
 - 5: Upon receiving ("Confirm", session-id) from Adversary: ▷ Step 4
 - 6: Send-Receiver(Sender, Message); ▷ Step 5
-

Algorithm 4 Compute Example Workflow (full version in Algorithm 13)

- 1: Upon receiving (Receiver, "Delete Node", session-id, node-id, $creds$) from \mathcal{F}_{ExtNet} : ▷ Step 5
 - 2: Send- $\mathcal{F}_{SMT}(\mathcal{F}_{Compute}, \mathcal{F}_{Identity}, \text{"Service Validation"}, \text{session-id}, creds_{compute}, creds, \text{"Delete node-id"})$; ▷ Step 6
 - 3:
 - 4: Upon receiving ($\mathcal{F}_{Identity}$, "Service Validated", session-id, user-id, service-id, Request, valid) from \mathcal{F}_{SMT} : ▷ Step 13
 - 5: **if** valid & a node with id=node-id exists **then**
 - 6: Delete node with id=node-id;
 - 7: Send- $\mathcal{F}_{ExtNet}(\mathcal{F}_{Compute}, Receiver, \text{"Delete Node"}, \text{session-id}, \text{node-id}, \text{Successful})$; ▷ Step 14
 - 8: **else**
 - 9: Send- $\mathcal{F}_{ExtNet}(\mathcal{F}_{Compute}, Receiver, \text{"Delete Node"}, \text{session-id}, \text{node-id}, \text{Fail})$; ▷ Alternate Step 14
 - 10: **end if**
-

Algorithm 5 SMT Example Workflow (full version in Algorithm 12)

- 1: Upon receiving ($Sender, Receiver, Message$): ▷ Steps 6, 10
 - 2: Create New-Message by removing the credentials and replacing them by their IDs;
 - 3: Send-Adversary(Sender, Receiver, New-Message); ▷ Steps 7,11
 - 4:
 - 5: Upon receiving ("Confirm", session-id) from Adversary: ▷ Steps 8, 12
 - 6: Send-Receiver(Sender, Message); ▷ Steps 13, 9
-

Algorithm 6 Identity Example Workflow (full version in Algorithm 24)

```
1: Upon receiving (Receiver, "Service Validation", session-id,  $creds_{service}$ ,  $creds$ , Request) from  $\mathcal{F}_{SMT}$ : ▷ Step 9
2: if  $creds_{service}$  &  $creds$  are valid &  $creds$  is allowed to perform the Request then
3:   valid=True;
4: else
5:   valid=False;
6: end if
7: Send- $\mathcal{F}_{SMT}$  ( $\mathcal{F}_{Identity}$ , Receiver, "Service Validated", session-id, user-id, service-id, Request, valid); ▷ Step 10
```

Algorithm 7 Corrupted Compute

```
1: function RECEIVEMESSAGE
2:   Upon receiving (Source, message) from  $\mathcal{F}_{SMT} \setminus \mathcal{F}_{ExtNet}$ :
3:   Send- $\mathcal{F}_{SMT}$  (source, Adversary, message);
4: end function
5:
6: function SENDMESSAGE
7:   Upon receiving (Adversary, "Forward", message, destination) from  $\mathcal{F}_{SMT}$ :
8:   Send- $\mathcal{F}_{SMT}$  ( $\mathcal{F}_{Compute}$ , destination, message);
9: end function
10:
11: function MAIN
12:   Upon receiving a message which does not contain "Forward" & Source=Adversary from  $\mathcal{F}_{SMT}$ :
13:   Apply the request;
14:   Send- $\mathcal{F}_{SMT}$  ( $\mathcal{F}_{Compute}$ , Adversary, result of the request);
15: end function
```

4 Basic Security of OpenStack

The goal of this section is to analyze the security of OpenStack in the universal composability setting, specially, we want to prove the following theorem:

Theorem 2. *The OpenStack Services protocol from §3.5 UC-realizes the Ideal Cloud \mathcal{F}_{Cloud} from §3.4 in the $(\mathcal{F}_{ExtNet}, \mathcal{F}_{SMT})$ -hybrid model.*

In order to prove this theorem, we need to:

- formally specify the ideal cloud and OpenStack Service in UC syntax
- provide a simulator and
- analyze that the simulator works to insure that the views of the environment is the same in both worlds.

The remaining subsections of this section are exactly to cover these purposes. Here, we define the terminologies that have been used in the rest of this paper.

- session-id: A unique value which is concatenation of user identity U and an incremental number. The uniqueness of the session-id is evaluated in each functionality before sending to the request-message.
- Buffer: In order to be able to track a request, components needs to store the information related to that request. This is done by storing this information in Buffer and updating, finding or removing them later on.
- confirmation message: Represents the adversarial interruption. The adversary may:
 - *Permit* the packet to be sent to the destination by sending a confirmation message for that session
 - *Delay* the packet by sending the confirmation message with delay or
 - *Drop* the packet by not sending the confirmation message at all.

4.1 Ideal Cloud Functionality Using Bearer Tokens

Algorithm 8³ represents \mathcal{F}_{Cloud} ; the ideal cloud using bearer token in the case of service corruption. \mathcal{F}_{Cloud} stores information related to corrupted services (Note that in this case, the services are only names for the corruption operation that is done by adversary) to be able to respond to the ideal-model adversary (i.e., to the simulator) in the case of corruption. Since the ideal cloud is a monolithic functionality, in the case on compromises it behave as if different components (services), such as Compute or Storage, have been corrupted despite not being composed of distinct parts. It does this by providing special interfaces for the simulator which allow it to request token validation or images if the environment has asked to corrupt some of the services. Additionally, if a portion of the cloud is corrupted it may cease to perform validation checks for its requests.

³The description of notation used in the algorithm is provided in appendix A

Algorithm 8 Ideal Cloud with corrupted services for bearer token

```
1: function CLOUD
2:   Upon receiving ("Corrupt", Service, value) from Sim:
3:   Corrupt[Service]=value; % the default value=None. None indicates no corruption; Passive
   is the partial corruption, and Active is the full corruption
4:   if Service= $\mathcal{F}_{Image}$  & value!=None then
5:     if there are user requests that have not finalized then
6:       Add (user-id) to the List;
7:     end if
8:     send-Sim(DB of (image-id, corresponding-Image),List of (user-id));
9:   else if Service= $\mathcal{F}_{Compute}$  & value!=None then
10:    if there are user requests that have not finalized then
11:      Add (user-id) to the List;
12:      Send-Sim(List of (user-id));
13:    end if
14:  else if Service= $\mathcal{F}_{Identity}$  & value!=None then
15:    Send-Sim(DB of (user-id, roles));
16:  else if Service= $\mathcal{F}_{BlockStorage}$  & value!=None then
17:    if there are user requests that have not finalized then
18:      Add (user-id) to the List;
19:    end if
20:    Send-Sim(List of (user-id));
21:  else if Service= $\mathcal{F}_{Node}$ node-id & value!=None then
22:    if there are user requests that have not finalized then
23:      Add (user-id) to the List;
24:    end if
25:    Send-Sim(List of (user-id));
26:  else if Service= $\mathcal{F}_{Volume}$ volume-id & value!=None then
27:    if there are user requests that have not finalized then
28:      Add (user-id) to the List;
29:    end if
30:    Send-Sim(List of (user-id));
31:  end if
32:  Upon receiving (Receiver, "Access Node", session-id, creds, node-id, RequestActivity) from
   user U:
33:  if session-id =(U,N) where N non-repetitive for user U then
34:    StoreBuffer (Receiver, "Access Node", session-id, creds, node-id, RequestActivity);
35:  end if
36:  Send-Sim (Receiver, "Node Access", session-id, user-id, node-id, RequestActivity);
37:
38:
39:  Upon receiving("Result Access Node", session-id) from Sim:
40:  if FindBuffer(Receiver, "Access Node", session-id, creds, node-id, RequestActivity, valid)
   then
41:    if valid=True then
42:      results  $\leftarrow$  EXECUTE(AccessRequest);
```

```

43:     UpdateBuffer({Receiver, "Access Node", session-id, creds, node-id, RequestActivity,
valid}, {Receiver, "Access Node", session-id, creds, node-id, result, valid});
44:     Send-Sim ("Access Node", session-id, user-id, node-id, result, valid);
45:     end if
46: end if
47: Upon receiving("Output Access Node", session-id) from Sim:
48: if FindBuffer(Receiver, "Access Node", session-id, creds, node-id, results, valid) then
49:     Valid=valid;
50:     RemoveBuffer("Access Node", session-id, creds, node-id, results, valid);
51:     Output("Access Node", session-id, results, Valid) to Receiver;
52: end if
53:
54: Upon receiving ("Access Node", session-id, node-id, RequestActivity) from Sim:
55: if Corrupt[Node node-id ]=Active then
56:     results ← EXECUTE(AccessRequest);
57: else
58:     results = None
59: end if
60: Send-Sim("Access Node", session-id, node-id, RequestActivity, results)
61: Upon receiving (Receiver, "Attach Volume", session-id, creds, volume-id, node-id) from user
U;
62: if session-id =(U,N) where N non-repetitive for user U then
63:     StoreBuffer(Receiver, "Attach Volume", session-id, creds, volume-id, node-id);
64: end if
65: Send-Sim(Receiver, "Attach Volume", session-id, volume-id, node-id);
66:
67: Upon receiving ("Result Attach Volume", session-id) from Sim:
68: if FindBuffer(Receiver, "Attach Volume", session-id, creds, volume-id, node-id, valid) then
69:     if valid=True AND attached-volume for node node-id is None AND attached-node for
volume volume-id is None then
70:         Set attached-volume for node node-id to volume-id
71:         Set attached-node for volume volume-id to node-id
72:         UpdateBuffer({Receiver, "Attach Volume", session-id, creds, volume-id, node-id,
valid) }, {Receiver, "Attach Volume", session-id, creds, volume-id, node-id, success })
73:         Send-Sim("Attach Volume", session-id, volume-id, node-id, success)
74:     else
75:         UpdateBuffer({Receiver, "Attach Volume", session-id, creds, volume-id, node-id,
valid) }, {Receiver, "Attach Volume", session-id, creds, volume-id, node-id, failure) })
76:         Send-Sim("Attach Volume", session-id, volume-id, node-id, failure)
77:     end if
78: end if
79:

```

```

80:   Upon receiving ("Output Attach Volume", session-id) from Sim:
81:   if FindBuffer(Receiver, "Attach Volume", session-id, creds, volume-id, node-id, success)
      then
82:       RemoveBuffer(Receiver, "Attach Volume", session-id, creds, volume-id, node-id, success)
83:       Output("Attach Volume", session-id, success) to Receiver
84:   else if FindBuffer(Receiver, "Attach Volume", session-id, creds, volume-id, node-id, failure)
      then
85:       RemoveBuffer(Receiver, "Attach Volume", session-id, creds, volume-id, node-id, failure)
86:       Output("Attach Volume", session-id, failure) to Receiver
87:   end if
88:
89:   Upon Receiving (Confirm, "Attach Volume" session-id, valid)
90:   if FindBuffer(Receiver, "Attach Volume", session-id, creds, volume-id, node-id) then
91:       if user user-id is allowed to attach volume-id to node-id then
92:           valid=True
93:       else
94:           valid=False
95:       end if
96:       if Corrupt[Identity]=Active then
97:           valid = value sent by Sim
98:       end if
99:       UpdateBuffer({Receiver, "Attach Volume", session-id, creds, volume-id, node-id },
100:      {Receiver, "Attach Volume", session-id, creds, volume-id, node-id, valid })
101:       Send-Sim(Receiver, "Attach Volume", session-id, volume-id, node-id, valid)
102:   end if
103:
104:   Upon receiving ("Attach Volume", session-id, volume-id, node-id) from Sim;
105:   if Corrupt[Compute]=Active OR Corrupt[Node node-id ]=Active then
106:       Set attached-volume for node node-id to volume-id
107:   end if
108:   if Corrupt[Storage]=Active OR Corrupt[Volume volume-id ]=Active then
109:       Set attached-node for volume volume-id to node-id
110:   end if
111:   Send-Sim ("Attach Volume", session-id, volume-id, node-id);
112:   Upon receiving (Receiver, "Detach Volume", session-id, creds, volume-id, node-id) from
      user U;
113:   if session-id =(U,N) where N non-repetitive for user U then
114:       StoreBuffer(Receiver, "Detach Volume", session-id, creds, volume-id, node-id);
115:   end if
116:   Send-Sim(Receiver, "Detach Volume", session-id, volume-id, node-id);
117:
118:   Upon receiving ("Result Detach Volume", session-id) from Sim:
119:   if FindBuffer(Receiver, "Detach Volume", session-id, creds, volume-id, node-id, valid) then

```

```

119:     if valid=True AND attached-volume for node node-id is volume-id AND attached-node
      for volume volume-id is node-id then
120:         Set attached-volume for node node-id to None
121:         Set attached-node for volume volume-id to None
122:         UpdateBuffer({Receiver, "Detach Volume", session-id, creds, volume-id, node-id,
      valid) }, {Receiver, "Detach Volume", session-id, creds, volume-id, node-id, success })
123:         Send-Sim("Detach Volume", session-id, volume-id, node-id, success)
124:     else
125:         UpdateBuffer({Receiver, "Detach Volume", session-id, creds, volume-id, node-id,
      valid) }, {Receiver, "Detach Volume", session-id, creds, volume-id, node-id, failure) })
126:         Send-Sim("Detach Volume", session-id, volume-id, node-id, failure)
127:     end if
128: end if
129:
130: Upon receiving ("Output Detach Volume", session-id) from Sim:
131: if FindBuffer(Receiver, "Detach Volume", session-id, creds, volume-id, node-id, success)
      then
132:     RemoveBuffer(Receiver, "Detach Volume", session-id, creds, volume-id, node-id, suc-
      cess)
133:     Output("Detach Volume", session-id, success) to Receiver
134: else if FindBuffer(Receiver, "Detach Volume", session-id, creds, volume-id, node-id, fail-
      ure) then
135:     RemoveBuffer(Receiver, "Detach Volume", session-id, creds, volume-id, node-id, failure)
136:     Output("Detach Volume", session-id, failure) to Receiver
137: end if
138: Upon Receiving (Confirm, "Detach Volume" session-id, valid)
139: if FindBuffer(Receiver, "Detach Volume", session-id, creds, volume-id, node-id) then
140:     if user user-id is allowed to detach volume-id from node-id then
141:         valid=True
142:     else
143:         valid=False
144:     end if
145:     if Corrupt[Identity]=Active then
146:         valid = value sent by Sim
147:     end if
148:     UpdateBuffer({Receiver, "Detach Volume", session-id, creds, volume-id, node-id },
      {Receiver, "Detach Volume", session-id, creds, volume-id, node-id, valid })
149:     Send-Sim(Receiver, "Detach Volume", session-id, volume-id, node-id, valid)
150: end if
151:
152: Upon receiving ("Detach Volume", session-id, volume-id, node-id) from Sim;

```

```

153:   if Corrupt[Compute]=Active OR Corrupt[Node node-id ]=Active then
154:       Set attached-volume for node node-id to None
155:   end if
156:   if Corrupt[Storage]=Active OR Corrupt[Volume volume-id ]=Active then
157:       Set attached-node for volume volume-id to None
158:   end if
159:   Send-Sim ("Detach Volume", session-id, volume-id, node-id);
160:    $C_1$ – Upon receiving (Receiver, "Create Node", session-id, user-id, image-id, Node-
      Structure) from U:
161:       if Corrupt[Compute]!="Active" then
162:           if session-id =(U,N) where N non-repetitive for user U then
163:               StoreBuffer (Receiver, "Create Node", session-id, user-id, image-id, Node-
      Structure);
164:           end if
165:       end if
166:       Send-Sim(Receiver, "Create Node", session-id, user-id, image-id, Node-Structure);
167:
168:    $C_3I_{12}$ – Upon receiving ("Create Node Output", session-id) from Sim:
169:   if FindBuffer(Receiver, "Create Node Continue", session-id, node-id, valid) then
170:       Output("Node Created", session-id, node-id, valid) to Receiver;
171:   end if
172:
173:    $D_1$ – Upon receiving (Receiver, "Delete Node", session-id, node-id, user-id) from user U:
174:   if Corrupt[Compute]!="Active" then
175:       if session-id =(U,N) where N non-repetitive for user U then
176:           StoreBuffer (Receiver, "Delete Node", session-id, user-id, node-id);
177:       end if
178:   end if
179:   Send-Sim(Receiver, "Delete Node", session-id, user-id, node-id);
180:
181:   Upon receiving ("Output Delete Node", session-id) from Sim:
182:   if FindBuffer(Receiver, "Delete Node", session-id, user-id, node-id, Valid, NodeExist) then
183:       if NodeExist=0 or Valid=0 then
184:           Output("Delete Node", session-id, node-id, Fail) to Receiver;
185:       else
186:           Output("Delete Node", session-id, node-id, Successful) to Receiver;
187:       end if
188:   end if

```

```

189:   Upon receiving ("Confirm", session-id) from Sim:
190:   if FindBuffer(Receiver, "Create Node", session-id, user-id, image-id, Node-Structure) then
191:       if user-id is valid & user-id is allowed to create node using Node-Structure then
192:           if Corrupt[Image]="Active" then
193:               UpdateBuffer({Receiver, "Create Node", session-id, user-id, image-id, Node-
Structure},{Receiver, "Create Node", session-id, user-id, "Corrupted Get Image", Node-
Structure})
194:                $C_3I_1$ – Send-Sim (Receiver, "Create Node", session-id, user-id, "Corrupted Get
Image");
195:           else
196:               if user-id is allowed to create node with image-id with Node-Structure & there
exists image-id then
197:                   Corresponding-Image=get the image corresponding to image-id;
198:                   UpdateBuffer({Receiver, "Create Node", session-id, user-id, image-id,
Node-Structure},{Receiver, "Get Node ID", session-id, user-id, image-id, Node-Structure,
Corresponding-Image});
199:                    $C_4I$ – Send-Sim(Receiver, "Get Node ID", session-id, user-id, image-id,
Corresponding-Image, Node-Structure);% GOTO  $C_5I$ 
200:               else
201:                   UpdateBuffer({Receiver, "Create Node", session-id, user-id, image-id, Node-
Structure},{Receiver, "Create Node Continue", session-id, NULL, Fail});
202:                    $C_4II$ – Send-Sim(Receiver, "Create Node", session-id, user-id, Fail, rea-
son="Get Image", Node-Structure); % GOTO  $C_5II$ 
203:               end if
204:           end if
205:       else
206:           UpdateBuffer({Receiver, "Create Node", session-id, user-id, image-id, Node-
Structure},{Receiver, "Create Node Continue", session-id, NULL, Fail});
207:            $C_4III$ – Send-Sim(Receiver, "Create Node", session-id, user-id, Fail, rea-
son="Create Node", Node-Structure); % GOTO  $C_5III$ 
208:       end if
209:   else if FindBuffer(Receiver, "Delete Node", session-id, user-id, node-id) then
210:       if user-id is valid & user-id is allowed to delete node node-id then
211:           Valid=1;
212:       else
213:           Valid=0;
214:       end if
215:       UpdateBuffer ({Receiver, "Delete Node", session-id, user-id, node-id },{Receiver,
"Delete Node", session-id, user-id, node-id, Valid});
216:        $D_4$ – Send-Sim (Receiver, "Delete Node", session-id, user-id, node-id, Valid);
217:   end if
218:
219:

```

```

220:   Upon receiving ("Service Validation", session-id, user-id, Request) from Sim:
221:   if Corrupt[Compute]="Active" or Corrupt[Image]="Active" OR Corrupt[Storage]=Active
      then
222:       if user-id is valid & user-id is allowed to apply Request then
223:           valid=1;
224:       else
225:           valid=0;
226:       end if
227:       Send-Sim("validation", user-id, session-id, Request, valid);
228:   end if
229:
230:    $D_3O_2$ – Upon receiving (Receiver, "Delete Node", session-id, node-id, valid) from Sim:
231:   if Corrupt[Compute]="Active" or Corrupt[Identity]="Active" then
232:       Output("Delete Node", session-id, node-id, valid) to Receiver;
233:   end if
234:    $D_3ID_4$ – Upon receiving ("Delete Node", session-id, node-id, valid) from Sim:
235:   if Flage-Identity="Active" & FindBuffer(Receiver, "Delete Node", session-id, user-id,
      node-id) then
236:       if valid=1 then
237:           if node node-id exists then
238:               NodeExist=1;
239:               Delete node with node-id;
240:           else
241:               NodeExist=0
242:           end if
243:           RemoveBuffer(Receiver, "Delete Node", session-id, user-id, node-id)
244:           Send-Sim (Receiver, "Delete Node Completed", session-id, user-id, node-id, valid,
      NodeExist);
245:       end if
246:   end if
247:    $AC_2$ – Upon receiving ("MainComputeCorrupt", request) from Sim:
248:   if Corrupt[Compute]="Active" then
249:       Apply the request;
250:       Send-Sim (MainComputeCorruptResult, result);
251:   end if
252:
253:    $C_3C_1O_2$ – Upon receiving (Receiver, "Create Node result", session-id, node-id, valid) from
      Sim:
254:   if Corrupt[Compute]="Active" then
255:       Output ("Node Created", session-id, node-id, valid) to Receiver;
256:   end if
257:
258:    $C_3I_9$ – Upon receiving (Receiver, "Node ID", session-id, user-id, image-id, "Corrupted Get
      Image", Corresponding-Image, node-id) from Sim:
259:   if Corrupt[Image]="Active" & FindBuffer(Receiver, "Create Node", session-id, user-id,
      "Corrupted Get Image", Node-Structure) then
260:

```

```

261:
262:     if node-id is not used then
263:         UpdateBuffer({Receiver, "Create Node", session-id, user-id, "Corrupted Get Im-
age", Node-Structure}, {Receiver, "Create Node Continue", session-id, node-id, Successful});
264:         Add (node-id, user-id, Corresponding-Image, Node-Structure) to the list of active
nodes;
265:         Send-Sim("Create Node Continue", session-id, user-id, successful);
266:     else
267:         UpdateBuffer({Receiver, "Get Node ID", session-id, user-id, image-id, Node-
Structure,, Corresponding-Image}, {Receiver, "Create Node Continue", session-id, node-id,
Fail});
268:         Send-Sim("Create Node Continue", session-id, user-id, Fail); %GOTO  $C_3I_{10}$ 
269:     end if
270: end if
271:
272:  $C_3C_1I_2$ – Upon receiving ("Get Image", session-id, user-id, image-id) from Sim:
273: if Corrupt[Compute]="Active" then
274:     if user-id is valid & user-id is allowed to apply Request then
275:         valid=1;
276:         if image image-id exists then
277:             Corresponding-Image= extract corresponding image of image-id;
278:         else
279:             Corresponding-Image=NULL;
280:         end if
281:     else
282:         valid=0;
283:         Corresponding-Image=NULL;
284:     end if
285:     Send-Sim("Get Image", session-id, user-id, image-id, Corresponding-Image,
valid);%GOTO  $C_3C_1I_3$ 
286: end if
287:
288:  $C_3ID_8$ – Upon receiving ("Get Image", session-id, image-id) from Sim:
289: if Corrupt[Identity]="Active" then
290:     if image image-id exists then
291:         Corresponding-Image= extract corresponding image of image-id;
292:     else
293:         Corresponding-Image=NULL;
294:     end if
295:     Send-Sim("Get Image", session-id, image-id, Corresponding-Image);
296: end if
297:
298:  $C_3ID_{12}$ – Upon receiving ("Node ID", session-id, node-id, Corresponding-Image) from Sim:
299: if Corrupt[Identity]="Active" & FindBuffer(Receiver, "Create Node", session-id, user-id,
image-id, Node-Structure) then
300:

```

```

301:
302:     if node-id is not used then
303:         Add( node-id, user-id, Node-Structure, Corresponding-Image) to the list of active
        nodes;
304:         UpdateBuffer({Receiver, "Create Node", session-id, user-id, image-id, Node-
        Structure}, {Receiver, "Create Node Continue, session-id, node-id, Successful});
305:         Send-Sim("Create Node Continue", session-id, user-id, Successful);%GOTO  $C_3I_{10}$ 
306:     else
307:         UpdateBuffer({Receiver, "Create Node", session-id, user-id, image-id, Node-
        Structure}, {Receiver, "Create Node Continue, session-id, node-id, Fail});
308:         Send-Sim("Create Node Continue", session-id, user-id, Fail);%GOTO  $C_3I_{10}$ 
309:     end if
310: end if
311:
312:  $C_3ID_5^*$ – Upon receiving ("Create Node Output valid", session-id, valid) from Sim:
313: if Corrupt[Identity]="Active" & FindBuffer(Receiver, "Create Node", session-id, user-id,
        image-id, Node-Structure) then
314:     if valid=0 then
315:         Output("Create Node", session-id, NULL, Fail) to Receiver;
316:     end if
317: end if
318:  $D_8$ – Upon receiving ("Delete Node", session-id, Continue) from Sim:
319: if FindBuffer(Receiver, "Delete Node", session-id, user-id, node-id, Valid) then
320:     if there is node with node-id then
321:         NodeExist=1;
322:     else
323:         NodeExist=0;
324:     end if
325:     UpdateBuffer({Receiver, "Delete Node", session-id, user-id, node-id, Valid}, {Receiver,
        "Delete Node", session-id, user-id, node-id, Valid, NodeExist});
326:     if Valid=1 & NodeExist=1 then
327:         Delete node-id from the Node list;
328:     end if
329:     Send-Sim ("Delete Node Completed", session-id, Valid, NodeExist);
330: end if
331:
332:  $D_{11}$ – Upon receiving ("Output Delete Node", session-id) from Sim:
333: if FindBuffer(Receiver, "Delete Node", session-id, user-id, node-id, Valid, NodeExist) then
334:     if NodeExist=0 or Valid=0 then
335:         Output("Delete Node", session-id, node-id, Fail) to Receiver;
336:     else
337:         Output("Delete Node", session-id, node-id, Successful) to Receiver;
338:     end if
339: end if
340:

```

```

341:
342:    $C_{13I}$ – Upon receiving ("Node ID", session-id, node-id) from Sim:
343:   if FindBuffer(Receiver, "Get Node ID", session-id, user-id, image-id, Node-Structure,
    Corresponding-Image) then
344:       node-struct=Node-Structure;
345:       if node-id is not used then
346:           UpdateBuffer({Receiver, "Get Node ID", session-id, user-id, image-id, Node-
    Structure, Corresponding-Image}, {Receiver, "Create Node Continue", session-id, node-id, Suc-
    cessful});
347:           Add (node-id, user-id, Corresponding-Image, Node-Structure) to the list of active
    nodes;
348:           Send-Sim("Create Node Continue", session-id, user-id, successful);
349:       else
350:           UpdateBuffer({Receiver, "Get Node ID", session-id, user-id, image-id, Node-
    Structure,, Corresponding-Image}, {Receiver, "Create Node Continue", session-id, node-id,
    Fail});
351:           Send-Sim("Create Node Continue", session-id, user-id, Fail);
352:       end if
353:   end if
354:
355:    $C_{9III}, C_{13II}, C_{16I}$ – Upon receiving ("Create Node Output", session-id) from Sim:
356:   if FindBuffer(Receiver, "Create Node Continue", session-id, node-id, valid) then
357:       Output("Create Node", session-id, node-id, valid) to Receiver;
358:   end if
359: end function

```

4.2 OpenStack Services Functionalities Using Bearer Token

In this section different OpenStack Service functionalities are explained.

For full-corrupt (active adversary), the code needs to be replaced with the *corrupt-code*, this is done by "Corrupt" function. In this case, the actual code is replaced by the corrupt-code which has three main functions:

- Receive Message: whenever the service receives a message it will forward it to the adversary and gives the control to the adversary.
- Send Message: whenever the service receives a message from adversary which is meant to be forwarded to another service, it sends the message to the destination service on behalf of the corrupted service.
- Main: whenever the service receives a message from the adversary which is not a forwarding message, it will apply the request as the adversary asks to.

Dashboard: It's the interface between the user/Environment and services (Algorithm 9). It gets the input from user/Environment changes it into format that is understandable by services and adds user credentials and sends it to the requested service and vices versa.

Algorithm 9 Dashboard

```
1: function DASHBOARD
2:   Upon receiving Request-Message from Env:
3:   User U Creates ( $U_{Dashboard}$ ,  $F_{Service}$ , Request-Message,  $creds$ );
4:   Send- $\mathcal{F}_{ExtNet}(U_{Dashboard}, F_{Service}, \text{Request-Message}, creds)$ ;
5:
6:   Upon receiving (Sender, Output-Message) from  $\mathcal{F}_{ExtNet}$ :
7:   Output (Output-Message) to Env;
8: end function
```

External Network: Algorithm 10 represents the external network between the user/Environment and the cloud. In order to preserve confidentiality, whenever a message is received, the external network removes user credentials from the message and sends the shortened message to the adversary and waits for adversary. The request message will be forwarded to the destination whenever the adversary replies by confirmation message.

Dummy Adversary \mathcal{A} : We consider a dummy adversary, Algorithm 11, which by receiving any message, she will only forward it to the environment E and waits for the environments response. The environment may either send a confirmation message, arbitrary message or a message that informs a corruption to a service. Next the \mathcal{A} forwards the received message from E to destination which is either the external network or SMT.

Secure Message Transmission: SMT (Algorithm 12) is the algorithm that represents the internal message queue of the cloud. It handles the communication between services by protecting integrity and confidentiality. Services communicate with each other through SMT, thus, any message that is sent from one service to another is transmitted through SMT. In order to handle the adversarial interruption, SMT removes credentials from the original message and gives the control to \mathcal{A} by sending the shorten message. However, in the case of full-corruption (active adversary), the SMT will not remove the credential of the messages that are sent to the corrupted service.

Algorithm 10 External Network

```
1: function EXTERNALNETWORK
2:   Upon receiving (Sender, Receiver, Message):
3:     StoreBuffer(Sender, Receiver, Message);
4:     Create New-Message by removing the credentials and replacing them by their IDs; % i.e.
       Service-id, user-id
5:     Send-Adversary(Sender, Receiver, New-Message);
6:
7:   Upon receiving ("Confirm", session-id) from Adversary:
8:     if FindBuffer (Sender, Receiver, Message) where it's session ID=session-id then
9:       RemoveBuffer(Sender, Receiver, Message) where it's session-ID=session-id;
10:      Send-Receiver(Sender, Message);
11:     end if
12: end function
```

Algorithm 11 Dummy Adversary

```
1: function ADVERSARY
2:   Upon receiving (message) from  $\mathcal{F}_{ExtNet}/\mathcal{F}_{SMT}$ :
3:     Send-Env(message);
4:
5:   Upon receiving (message) from Env:
6:     Send- $\mathcal{F}_{ExtNet}/\mathcal{F}_{SMT}$  (message);
7:
8:   Upon receiving ("Corrupt", Service, value, Corrupt-Code) from Env:
9:     Send- $\mathcal{F}_{SMT}$  ("Corrupt", Service, value, Corrupt-Code);
10: end function
```

Algorithm 12 Secure Message Transmission

```
1: function SMT
2:   Upon receiving (Sender, Receiver, Message):
3:   if Sender=Adversary or Receiver=Adversary then
4:     Send-Receiver (Sender, Message);
5:   else
6:     StoreBuffer(Sender, Receiver, Message);
7:     if Flag-Sender=1 then
8:       Send-Adversary(Sender, Receiver, Message);
9:     else
10:      Create New-Message by removing the credentials and replacing them by their IDs;
11:      Send-Adversary(Sender, Receiver, New-Message);
12:    end if
13:  end if
14:
15:  Upon receiving (“Confirm”, session-id) from Adversary:
16:  if FindBuffer (Sender, Receiver, Message) where it’s session ID=session-id then
17:    RemoveBuffer(Sender, Receiver, Message);
18:    Send-Receiver(Sender, Message);
19:  end if
20:
21:  Upon receiving (“Corrupt”, Service, value, Corrupt-Code) from Adversary:
22:  if value=“Active” then
23:    Send-Service(“Corrupt”,Corrupt-Code);
24:  else
25:    Flag-Service=1;
26:  end if
27:
28: end function
```

Compute: Algorithm 13 represents compute service. This algorithm only covers "create node", "delete node", "access node", and "attach/detach volume" functionalities.

Create Node function: For a user to create a node, compute first checks with identity to determine whether the user is permitted to perform a create a node with the given structure and, if so, forwards the request to Image service. The image service will also check with identity to determine whether the user is permitted to access the image and, if so, returns the corresponding image back to compute. Based on the Image service result, the compute service may create the node and notify tge user with the result.

Delete Node function: For a user to delete a node, compute first checks with identity to determine whether the user is permitted to delete the node. If the user is allowed to delete the node and the node exists, compute deletes the node and notifies the user.

Access Node function: For a user to access a node compute first checks whether the user making the request is allowed to access the node and, if so, forwards the request to the intended node. The node will also check if the user issuing the request is allowed to make node accesses and will only execute the request if the user is permitted to do so. After completing or rejecting the request the node will return its response to compute which will forward it to the user who issued the request.

*Attach/Detach function:*In order to attach or detach a volume to/from a compute node a user issues a request to compute. Compute will check with identity to determine whether the user is permitted to perform attach/detach operations on that node and will request that the storage service make the volume available if so. The storage service will also validate the user's credentials and will only make the volume available if the user is permitted to attach/detach it. The storage service will then respond to compute and, if the volume is available, compute will indicate to the node that it should be attached/detached, and report the result to the user.

Corrupted Compute: Algorithm 14 represents compute service in full-corruption (active adversary). In this case, the actual code is replaced by the corrupt-code.

Image: Algorithm 15 represents only "get image" functionality of image service. Get Image functionality needs to access identity services for validating the the user and its request to get the image related to the image-id mentioned in the request-message.

Corrupted Image: Algorithm 16 represents image service in full-corruption (Active adversary).

BlockStorage: Algorithm 17 represents block storage service. This algorithm only covers "Attach/Detach volume" functionalities.

Attach/Detach Volume function: When compute service makes an attach/detach volume request, block storage first checks with identity to determine whether the user is permitted to perform attach/detach operations on that node. If the user is eligible and the volume-id exists, block storage makes a request to volume service to attach/detach the volume. The storage service will then respond to compute (if the volume is available).

Corrupted BlockStorage: Algorithm 18 represents block storage service in full-corruption (active adversary). In this case, the actual code is replaced by the corrupt-code.

Volume: Algorithm 19 represents Volume service. This algorithm only covers "Attach/Detach" and "access" functionalities.

Attach/Detach function: By receiving a request from block storage service, volume service makes sure that the volume-id is correct, then attaches/detaches the volume to/from the compute node.

Access Node function: This functionality performs the user's requested operation for a compute

Algorithm 13 Compute

```
1: function CORRUPT
2:   Upon receiving (“Corrupt”, Corrupt-Code) from Adv:
3:   Replace code of  $\mathcal{F}_{Compute}$  with code of Corrupted  $\mathcal{F}_{Compute}$ 
4: end function
5:
6: function (ATTACH/DETACH) VOLUME
7:   Upon receiving (Receiver, “(Attach/Detach) Volume”, session-id, creds, volume-id, node-id)
   from  $\mathcal{F}_{ExtNet}$ :
8:   StoreBuffer (Receiver, “(Attach/Detach) Volume”, session-id, creds, volume-id, node-id);
9:   Send- $\mathcal{F}_{SMT}$  ( $\mathcal{F}_{Compute}$ ,  $\mathcal{F}_{Identity}$ , “Service Validation”, session-id, credscompute, creds, “(At-
   tach/Detach) Volume”);
10:
11:   Upon receiving ( $\mathcal{F}_{Identity}$ , “Service Validated”, session-id, user-id, service-id, Request, valid)
   from  $\mathcal{F}_{SMT}$ :
12:   if FindBuffer(Receiver, “(Attach/Detach) Volume”, session-id, creds, volume-id, node-id)
   then
13:     if valid=True then
14:       UpdateBuffer({Receiver, “(Attach/Detach) Volume”, session-id, creds, volume-id,
   node-id }, {Receiver, “Storage (Attach/Detach) Volume”, session-id, creds, volume-id, node-id
   });
15:       Send- $\mathcal{F}_{SMT}$  ( $\mathcal{F}_{Compute}$ ,  $\mathcal{F}_{BlockStorage}$ , “(Attach/Detach) Volume”, session-id, creds,
   volume-id, node-id);
16:     else
17:       RemoveBuffer(Receiver, “(Attach/Detach) Volume”, session-id, creds, volume-id,
   node-id);
18:       Send- $\mathcal{F}_{ExtNet}$  ( $\mathcal{F}_{Compute}$ , Receiver, “(Attach/Detach) Volume”, session-id, volume-id,
   node-id, Fail);
19:     end if
20:   end if
21:
22:   Upon receiving ( $\mathcal{F}_{BlockStorage}$ , Result, session-id) from  $\mathcal{F}_{SMT}$ :
23:   if FindBuffer(Receiver, “Storage (Attach/Detach) Volume”, session-id, creds, volume-id,
   node-id) then
24:     if Result is Fail then
25:       RemoveBuffer(Receiver, “Storage (Attach/Detach) Volume”, session-id, creds,
   volume-id, node-id);
26:       Send- $\mathcal{F}_{ExtNet}$  ( $\mathcal{F}_{Compute}$ , Receiver, “(Attach/Detach) Volume”, session-id, volume-id,
   node-id, Fail);
27:     else
28:       UpdateBuffer({Receiver, “Storage (Attach/Detach) Volume”, session-id, creds,
   volume-id, node-id }, { $\mathcal{F}_{Compute}$ ,  $\mathcal{F}_{Node}$ , “(Attach/Detach) Volume”, session-id, volume-id, node-
   id });
29:       Send- $\mathcal{F}_{ExtNet}$  ( $\mathcal{F}_{Compute}$ ,  $\mathcal{F}_{Node}$ , “(Attach/Detach) Volume”, session-id, volume-id,
   node-id);
30:     end if
31:   end if
```

```

32:
33:   Upon receiving ( $\mathcal{F}_{Node}$ , "(Attach/Detach) Volume", session-id, Result) from  $\mathcal{F}_{SMT}$ :
34:   if FindBuffer( $\mathcal{F}_{Compute}$ ,  $\mathcal{F}_{Node}$ , "(Attach/Detach) Volume", session-id, volume-id, node-id)
then
35:     if Result is Fail then
36:       RemoveBuffer( $\mathcal{F}_{Compute}$ ,  $\mathcal{F}_{Node}$ , "(Attach/Detach) Volume", session-id, volume-id,
node-id);
37:       Send- $\mathcal{F}_{ExtNet}$  ( $\mathcal{F}_{Compute}$ , Receiver, "(Attach/Detach) Volume", session-id, volume-id,
node-id, Fail);
38:     else
39:       RemoveBuffer( $\mathcal{F}_{Compute}$ ,  $\mathcal{F}_{Node}$ , "(Attach/Detach) Volume", session-id, volume-id,
node-id);
40:       Send- $\mathcal{F}_{ExtNet}$  ( $\mathcal{F}_{Compute}$ ,  $\mathcal{F}_{Node}$ , "(Attach/Detach) Volume", session-id, volume-id,
node-id), Success;
41:     end if
42:   end if
43: end function
44:
45: function ACCESSNODE
46:   Upon receiving (Receiver, "Access Node", session-id, node-id, RequestActivity, creds):
47:   StoreBuffer(Receiver, "Node Access", session-id, node-id, user-id, RequestActivity) from
 $\mathcal{F}_{ExtNet}$ ;
48:   if node-id is in list of active Nodes & user user-id is allowed to access node-id then
49:     UpdateBuffer({Receiver, "Node Access", session-id, node-id, user-id, RequestActiv-
ity},{Receiver, "Execute Node Access", session-id, node-id, user-id });
50:     Send-SMT( $\mathcal{F}_{Compute}$ ,  $\mathcal{F}_{Node}$ , "Execute Access Node", session-id, user-id, node-id, Re-
questActivity);
51:   else
52:     RemoveBuffer(Receiver, "Node Access", session-id, node-id, user-id, RequestActivity);
53:     Send- $\mathcal{F}_{ExtNet}$  ( $\mathcal{F}_{Compute}$ , Receiver, "Access Node", session-id, NULL, Fail);
54:   end if
55:
56:   Upon receiving ( $\mathcal{F}_{Node}$ , "Node Accessed", session-id, results, valid) from  $\mathcal{F}_{SMT}$ :
57:   if FindBuffer(Receiver, "Execute Node Access", session-id, node-id, user-id) then
58:     RemoveBuffer(Receiver, "Execute Node Access", session-id, node-id, user-id);
59:     Send- $\mathcal{F}_{ExtNet}$  ( $\mathcal{F}_{Compute}$ , Receiver, "Access Node", session-id, result, valid);
60:   end if
61: end function

```

```

62:
63: function CREATENODE
64:   Upon receiving (Receiver, “Create Node”,session-id, creds, image-id, Node-Structure) from
       $\mathcal{F}_{ExtNet}$ :
65:     StoreBuffer (Receiver, “Validate Create Node”, session-id, creds, image-id, Node-Structure);
66:     Send- $\mathcal{F}_{SMT}$  (  $\mathcal{F}_{Compute}$ ,  $\mathcal{F}_{Identity}$ , “Service Validation”, session-id, credscompute, creds, “Cre-
      ate Node”);
67:
68:   Upon receiving ( $\mathcal{F}_{Identity}$ , “Service Validated”, session-id, user-id, service-id, Request, valid)
      from  $\mathcal{F}_{SMT}$ :
69:     if FindBuffer(Receiver, “Validate Create Node”, session-id, creds, image-id, Node-Structure,
      node-id) then
70:       if valid=True then
71:         UpdateBuffer({Receiver, “Validate Create Node”, session-id, creds, image-id, Node-
          Structure, valid}, {Receiver, “Get Image Create Node”, session-id, creds, image-id, Node-
          Structure});
72:         Send- $\mathcal{F}_{SMT}$  ( $\mathcal{F}_{Compute}$ ,  $\mathcal{F}_{Image}$ , “Get Image”, session-id, creds, image-id);
73:       else
74:         RemoveBuffer(Receiver, “Validate Create Node”, session-id, creds, image-id, Node-
          Structure, valid);
75:         Send- $\mathcal{F}_{ExtNet}$  ( $\mathcal{F}_{Compute}$ , Receiver, “Node Created”, session-id, NULL, Fail);
76:       end if
77:     end if
78:
79:   Upon receiving ( $\mathcal{F}_{Image}$ , “Image”, session-id, image-id, Corresponding-Image ) from  $\mathcal{F}_{SMT}$ :
80:     if FindBuffer(Receiver, “Get Image Create Node”, session-id, creds, image-id, Node-
      Structure) then
81:       if Corresponding-Image = NULL then
82:         RemoveBuffer(Receiver, “Get Image Create Node”, session-id, creds, image-id, Node-
          Structure);
83:         Send- $\mathcal{F}_{ExtNet}$  ( $\mathcal{F}_{Compute}$ , Receiver, “Node Created”,session-id, NULL, Fail);
84:       else

```

```

85:         UpdateBuffer({Receiver, "Get Image Create Node", session-id, creds, image-id,
Node-Structure},{Receiver, "Request Node ID", session-id, creds, image-id, Node-Structure})
86:         Send- $\mathcal{F}_{SMT}$  ( $\mathcal{F}_{Compute}$ , Adversary, "Request Node ID", session-id);
87:     end if
88: end if
89:
90:     Upon receiving (Adversary, "Node ID", session-id, node-id) from  $\mathcal{F}_{SMT}$ :
91:     if FindBuffer(Receiver, "Request Node ID", session-id, creds, image-id, Node-Structure)
then
92:         node-struct=Node-Structure;
93:         RemoveBuffer(Receiver, "Request Node ID", session-id, creds, image-id, Node-
Structure);
94:         if node-id is not used then
95:             Add (node-id, user-id, node-struct) to the list of active nodes;
96:             Send- $\mathcal{F}_{ExtNet}$  ( $\mathcal{F}_{Compute}$ , Receiver, "Node Created", session-id, node-id, Successful);
97:         else
98:             Send- $\mathcal{F}_{ExtNet}$  ( $\mathcal{F}_{Compute}$ , Receiver, "Node Created", session-id, node-id, Fail);
99:         end if
100:     end if
101: end function
102:
103:
104: function DELETENODE
105:     Upon receiving (Receiver, "Delete Node", session-id, node-id, creds) from  $\mathcal{F}_{ExtNet}$ :
106:     StoreBuffer (Receiver, "Validate Delete Node", session-id, creds, node-id);
107:     Send- $\mathcal{F}_{SMT}$  ( $\mathcal{F}_{Compute}$ ,  $\mathcal{F}_{Identity}$ , "Service Validation", session-id, credscompute, creds, "Delete
node-id ");
108:
109:     Upon receiving ( $\mathcal{F}_{Identity}$ , "Service Validated", session-id, user-id, service-id, Request, valid)
from  $\mathcal{F}_{SMT}$ :
110:     if FindBuffer(Receiver, "Validate Delete Node", session-id, creds, node-id) then
111:         node-ID=node-id;
112:         RemoveBuffer(Receiver, "Validate Delete Node", session-id, creds, node-id);
113:         if valid=True & there is node with node-ID then
114:             Delete node with node-ID;
115:             Send- $\mathcal{F}_{ExtNet}$  ( $\mathcal{F}_{Compute}$ , Receiver, "Delete Node", session-id, node-ID, Successful);
116:         else
117:             Send- $\mathcal{F}_{ExtNet}$  ( $\mathcal{F}_{Compute}$ , Receiver, "Delete Node", session-id, node-ID, Fail);
118:         end if
119:     end if
120: end function

```

Algorithm 14 Corrupted Compute

```
1: function RECEIVEMESSAGE
2:   Upon receiving (Source, message) from  $\mathcal{F}_{SMT} \setminus \mathcal{F}_{ExtNet}$ :
3:   Send- $\mathcal{F}_{SMT}$  (source, Adversary, message);
4: end function
5:
6: function SENDMESSAGE
7:   Upon receiving (Adversary, "Forward", message, destination) from  $\mathcal{F}_{SMT}$ :
8:   Send- $\mathcal{F}_{SMT}$  ( $\mathcal{F}_{Compute}$ , destination, message);
9: end function
10:
11:
12: function MAIN
13:   Upon receiving a message which does not contain "Forward" & Source=Adversary from
       $\mathcal{F}_{SMT}$ :
14:   Apply the request;
15:   Send- $\mathcal{F}_{SMT}$  ( $\mathcal{F}_{Compute}$ , Adversary, result of the request);
16: end function
```

Algorithm 15 Image

```
1: function CORRUPT
2:   Upon receiving ("Corrupt", Corrupt-Code) from Adv:
3:   Replace code of  $\mathcal{F}_{Image}$  with code of Corrupted  $\mathcal{F}_{Image}$ 
4: end function
5: function GETIMAGE
6:   Upon receiving ( $\mathcal{F}_{Compute}$ , "Get Image", session-id, creds, image-id) from  $\mathcal{F}_{SMT}$ :
7:   if session-id =(U,N) where N non-repetitive for user U then
8:     StoreBuffer( $\mathcal{F}_{Compute}$ , "Get Image", session-id, creds, image-id);
9:     Send- $\mathcal{F}_{SMT}$  ( $\mathcal{F}_{Image}$ ,  $\mathcal{F}_{Identity}$ , "Service Validation", session-id, credsImage, creds, "Get
      Image image-id ");
10:   end if
11:
12:   Upon receiving ( $\mathcal{F}_{Identity}$ , "Service Validated", session-id, user-id, service-id, Request, valid)
      from  $\mathcal{F}_{SMT}$ :
13:   if FindBuffer( $\mathcal{F}_{Compute}$ , "Get Image", session-id, creds, image-id) then
14:     Image-ID=image-id;
15:     RemoveBuffer(Receiver, "Get Image", session-id, creds, image-id);
16:     if valid=False OR No such image-id then
17:       Corresponding-Image=NULL;
18:     else
19:       Corresponding-Image=extract the corresponding image for Image-ID;
20:     end if
21:     Send- $\mathcal{F}_{SMT}$  ( $\mathcal{F}_{Image}$ ,  $\mathcal{F}_{Compute}$ , "Image", session-id, Image-ID, Corresponding-Image );
22:   end if
23: end function
```

Algorithm 16 Corrupted Image

```
1: function RECEIVEMESSAGE
2:   Upon receiving (Source, message) from  $\mathcal{F}_{SMT} \setminus \mathcal{F}_{ExtNet}$ :
3:   Send- $\mathcal{F}_{SMT}$  (source, Adversary , message);
4: end function
5:
6: function SENDMESSAGE
7:   Upon receiving (Adversary, “Forward”, message, destination) from  $\mathcal{F}_{SMT}$ :
8:   Send- $\mathcal{F}_{SMT}$  ( $\mathcal{F}_{Image}$ , destination, message);
9: end function
10:
11:
12: function MAIN
13:   Upon receiving a message which does not contain “Forward” & Source=Adversary from
      $\mathcal{F}_{SMT}$ :
14:   Apply the request;
15:   Send- $\mathcal{F}_{SMT}$  ( $\mathcal{F}_{Compute}$ , Adversary, result of the request);
16: end function
```

node.

Corrupted Volume: Algorithm 20 represents volume service in full-corruption (active adversary). In this case, the actual code is replaced by the corrupt-code.

ExecuteRequest function: When compute service forwards an execution-request on behalf of the user to the intended node, the node will check if the user is allowed to make node accesses and if so, executes the request. After completing or rejecting the request the node will return its response to compute.

Attach/Detach function: When the compute service indicate to the node that it should attach/detach a specific volume, the node attaches/detaches the volume and notifies the compute.

Partially Corrupted Node: Algorithm `refalg:PartiallyCorruptIdealNode` represents Node’s partial corruption (passive adversary). In this situation, some information are leaked to the adversary.

Fully Corrupted Node: Algorithm 23 represents Node in full-corruption (active adversary). In this case, the actual code is replaced by the corrupt-code..

Identity: Algorithm 24 gets validation request and validates the request based on its stored information.

Corrupted Identity: Algorithm 25 represents identity service in full-corruption (active adversary). In this case, the actual code is replaced by the corrupt-code.

Algorithm 17 BlockStorage

```
1: function CORRUPT
2:   Upon receiving (“Corrupt”, Corrupt-Code) from Adv:
3:   Replace code of  $\mathcal{F}_{BlockStorage}$  with code of Corrupted  $\mathcal{F}_{BlockStorage}$ 
4: end function
5: function ATTACHVOLUME
6:   Upon receiving (Source, “Attach Volume”, session-id, creds, volume-id, node-id)
7:   if Source is  $\mathcal{F}_{Compute}$  then
8:     if session-id =(U,N) where N non-repetitive for user U then
9:       StoreBuffer(Source, “Attach Volume”, session-id, creds, volume-id, node-id);
10:      Send- $\mathcal{F}_{SMT}$  ( $\mathcal{F}_{BlockStorage}$ ,  $\mathcal{F}_{Identity}$ , “Service Validation”, session-id, creds_{Block}, creds,
    “Attach Volume volume-id to node node-id ”);
11:     end if
12:     Upon receiving ( $\mathcal{F}_{Identity}$ , “Service Validated”, session-id, user-id, service-id, Request,
    valid) from  $\mathcal{F}_{SMT}$ :
13:     if FindBuffer(Source, “Attach Volume”, session-id, creds, volume-id, node-id) then
14:       RemoveBuffer(Source, “Attach Volume”, session-id, creds, volume-id, node-id);
15:       if valid=False OR No such volume-id then
16:         Send- $\mathcal{F}_{SMT}$  ( $\mathcal{F}_{BlockStorage}$ , Source, “Fail”, session-id, volume-id, node-id);
17:       else
18:         StoreBuffer( $\mathcal{F}_{Identity}$ , “Service Validated”, session-id, user-id, service-id, Request,
    valid)
19:         Send- $\mathcal{F}_{SMT}$  ( $\mathcal{F}_{BlockStorage}$ ,  $\mathcal{F}_{Volume}$ , “Attach”, session-id, volume-id, node-id);
20:         Upon receiving ( $\mathcal{F}_{Volume}$ , Response, session-id, volume-id, node-id) from  $\mathcal{F}_{SMT}$ :
21:         FindBuffer( $\mathcal{F}_{Identity}$ , “Service Validated”, session-id, user-id, service-id, Request,
    valid);
22:         if Request not in Buffer then
23:           Ignore message
24:         else
25:           RemoveBuffer( $\mathcal{F}_{Identity}$ , “Service Validated”, session-id, user-id, service-id, Re-
    quest, valid);
26:           Send- $\mathcal{F}_{SMT}$  ( $\mathcal{F}_{BlockStorage}$ , Source, Response, session-id, volume-id, node-id);
27:         end if
28:       end if
29:     end if
30:   else
31:     Drop message
32:   end if
33: end function
```

```

34: function DETACHVOLUME
35:   Upon receiving (Source, “Detach Volume”, session-id, creds, volume-id, node-id)
36:   if Source is  $\mathcal{F}_{Compute}$  then
37:     if session-id =(U,N) where N non-repetitive for user U then
38:       StoreBuffer(Source, “Detach Volume”, session-id, creds, volume-id, node-id);
39:       Send- $\mathcal{F}_{SMT}$  ( $\mathcal{F}_{BlockStorage}$ ,  $\mathcal{F}_{Identity}$ , “Service Validation”, session-id, creds_{Block}, creds,
“Detach Volume volume-id from Node node-id ”);
40:     end if
41:     Upon receiving ( $\mathcal{F}_{Identity}$ , “Service Validated”, session-id, user-id, service-id, Request,
valid) from  $\mathcal{F}_{SMT}$ :
42:     if FindBuffer(Source, “Detach Volume”, session-id, creds, volume-id) then
43:       RemoveBuffer(Source, “Get Volume”, session-id, creds, volume-id);
44:       if valid=False OR No such volume-id then
45:         Send- $\mathcal{F}_{SMT}$  ( $\mathcal{F}_{BlockStorage}$ , Source, “Fail”, session-id, volume-id, node-id);
46:       else
47:         StoreBuffer( $\mathcal{F}_{Identity}$ , “Service Validated”, session-id, user-id, service-id, Request,
valid)
48:         Send- $\mathcal{F}_{SMT}$  ( $\mathcal{F}_{BlockStorage}$ ,  $\mathcal{F}_{Volume}$ , “Detach”, session-id, volume-id, node-id);
49:         Upon receiving ( $\mathcal{F}_{Volume}$ , Response, session-id, volume-id, node-id) from  $\mathcal{F}_{SMT}$ :
50:         FindBuffer( $\mathcal{F}_{Identity}$ , “Service Validated”, session-id, user-id, service-id, Request,
valid);
51:         if Request not in Buffer then
52:           Ignore message
53:         else
54:           RemoveBuffer( $\mathcal{F}_{Identity}$ , “Service Validated”, session-id, user-id, service-id, Re-
quest, valid);
55:           Send- $\mathcal{F}_{SMT}$  ( $\mathcal{F}_{BlockStorage}$ , Source, Response, session-id, volume-id, node-id);
56:         end if
57:       end if
58:     end if
59:   else
60:     Drop message
61:   end if
62: end function

```

Algorithm 18 Corrupted BlockStorage

```

1: function RECEIVEMESSAGE
2:   Upon receiving (Source, message) from  $\mathcal{F}_{SMT} \setminus \mathcal{F}_{ExtNet}$ :
3:   Send- $\mathcal{F}_{SMT}$  (source, Adversary, message);
4: end function
5: function SENDMESSAGE
6:   Upon receiving (Adversary, “Forward”, message, destination) from  $\mathcal{F}_{SMT}$ :
7:   Send- $\mathcal{F}_{SMT}$  ( $\mathcal{F}_{BlockStorage}$ , destination, message);
8: end function

```

Algorithm 19 Volume

```
1: function CORRUPT
2:   Upon receiving (“Corrupt”, Corrupt-Code) from Adv:
3:   Replace code of  $\mathcal{F}_{Volume}$  with code of Corrupted  $\mathcal{F}_{Volume}$ 
4: end function
5: function ATTACH
6:   Upon receiving (Sender, “Attach”, session-id, user-id, volume-id, node-id) from  $\mathcal{F}_{SMT}$ :
7:   if Sender is  $\mathcal{F}_{BlockStorage}$  and volume-id is correct then
8:     Set AttachedNode=node-id;
9:     Send- $\mathcal{F}_{SMT}$  ( $\mathcal{F}_{Volume}$ ,  $\mathcal{F}_{BlockStorage}$ , “Success”, session-id);
10:  else
11:    Send- $\mathcal{F}_{SMT}$  ( $\mathcal{F}_{Volume}$ ,  $\mathcal{F}_{BlockStorage}$ , “Fail”, session-id);
12:  end if
13: end function
14: function DETACH
15:   Upon receiving (Sender, “Detach”, session-id, user-id, volume-id, node-id) from  $\mathcal{F}_{SMT}$ :
16:   if Sender is  $\mathcal{F}_{BlockStorage}$  and volume-id is correct and AttachedNode=node-id then
17:     Set AttachedNode=None;
18:     Send- $\mathcal{F}_{SMT}$  ( $\mathcal{F}_{Volume}$ ,  $\mathcal{F}_{BlockStorage}$ , “Success”, session-id);
19:   else
20:     Send- $\mathcal{F}_{SMT}$  ( $\mathcal{F}_{Volume}$ ,  $\mathcal{F}_{BlockStorage}$ , “Fail”, session-id);
21:   end if
22: end function
23: function ACCESS
24:   Upon receiving (Sender, “Access”, operation, session-id, user-id, volume-id, node-id) from
      $\mathcal{F}_{SMT}$ :
25:   if Sender is AttachedNode and volume-id is correct then
26:     perform operation
27:     Send- $\mathcal{F}_{SMT}$  ( $\mathcal{F}_{Volume}$ , Sender, “Success”, data requested, session-id);
28:   else
29:     Send- $\mathcal{F}_{SMT}$  ( $\mathcal{F}_{Volume}$ , Sender, “Fail”, session-id);
30:   end if
31: end function
```

Algorithm 20 Corrupted Volume

```
1: function RECEIVEMESSAGE
2:   Upon receiving (Source, message) from  $\mathcal{F}_{SMT} \setminus \mathcal{F}_{ExtNet}$ :
3:   Send- $\mathcal{F}_{SMT}$  (source, Adversary, message);
4: end function
5: function SENDMESSAGE
6:   Upon receiving (Adversary, “Forward”, message, destination) from  $\mathcal{F}_{SMT}$ :
7:   Send- $\mathcal{F}_{SMT}$  ( $\mathcal{F}_{Volume}$ , destination, message);
8: end function
9: function MAIN
10:  Upon receiving a message which does not contain “Forward” & Source=Adversary from
     $\mathcal{F}_{SMT}$ :
11:  Apply the request;
12:  Send- $\mathcal{F}_{SMT}$  ( $\mathcal{F}_{Compute}$ , Adversary, result of the request);
13: end function
```

Algorithm 21 Node

```
1: function CORRUPT
2:   Upon receiving (“Corrupt”, Corrupt-Code) from Adv:
3:   if type=’full’ then
4:     Replace code of  $\mathcal{F}_{Node}$  with code of Fully Corrupted  $\mathcal{F}_{Node}$ 
5:   else if type=’partial’ then
6:     Replace code of  $\mathcal{F}_{Node}$  with code of Partially Corrupted  $\mathcal{F}_{Node}$ 
7:   end if
8: end function
9: function ATTACH
10:  Upon receiving (Sender, “Attach”, volume-id) from  $\mathcal{F}_{SMT}$ :
11:  if Source is  $\mathcal{F}_{Compute}$  then
12:    if attached-volume is None then
13:      Set attached-volume to volume-id
14:      Send- $\mathcal{F}_{SMT}$  ( $\mathcal{F}_{Node}$ ,  $\mathcal{F}_{Compute}$ , “Attach Volume”, session-id, Success);
15:    else
16:      Send- $\mathcal{F}_{SMT}$  ( $\mathcal{F}_{Node}$ ,  $\mathcal{F}_{Compute}$ , “Detach Volume”, session-id, Fail);
17:    end if
18:  else
19:    drop message
20:  end if
21: end function
22:
23: function DETACH
24:  Upon receiving (Sender, “Detach”, volume-id) from  $\mathcal{F}_{SMT}$ :
25:  if Source is  $\mathcal{F}_{Compute}$  then
26:    if attached-volume is volume-id then
27:      Set attached-volume to None
28:      Send- $\mathcal{F}_{SMT}$  ( $\mathcal{F}_{Node}$ ,  $\mathcal{F}_{Compute}$ , “Detach Volume”, session-id, Success);
29:    else
30:      Send- $\mathcal{F}_{SMT}$  ( $\mathcal{F}_{Node}$ ,  $\mathcal{F}_{Compute}$ , “Detach Volume”, session-id, Fail);
31:    end if
32:  else
33:    drop message
34:  end if
35: end function
```

```

36: function EXECUTEREQUEST
37:   Upon receiving ( $\mathcal{F}_{Compute}$ , “Execute Access Node”, session-id, user-id, node-id, AccessRe-
    quest) from  $\mathcal{F}_{SMT}$ :
38:   if session-id =(U,N) where N non-repetitive for user U and U is the owner of the node then
39:     if AccessRequest requires data then
40:       StoreBuffer( $\mathcal{F}_{Node}$ ,  $\mathcal{F}_{Volume}$ , “Access”, data specified by AccessRequest, session-id,
        user-id, node-id)
41:       Send- $\mathcal{F}_{SMT}$  ( $\mathcal{F}_{Node}$ ,  $\mathcal{F}_{Volume}$ , “Access”, data specified by AccessRequest, session-id,
        user-id, volume-id, node-id)
42:       Upon receiving ( $\mathcal{F}_{Volume}$ ,  $\mathcal{F}_{Node}$ , “Success”, data, session-id) from  $\mathcal{F}_{SMT}$ :
43:         Store returned data
44:       end if
45:       results  $\leftarrow$  EXECUTE(AccessRequest);
46:       Send- $\mathcal{F}_{SMT}$  ( $\mathcal{F}_{Node}$ ,  $\mathcal{F}_{Compute}$ , “Node Accessed”, session-id, results, Successful);
47:     else
48:       Send- $\mathcal{F}_{SMT}$  ( $\mathcal{F}_{Node}$ ,  $\mathcal{F}_{Compute}$ , “Node Accessed”, session-id, None, Fail);
49:     end if
50: end function

```

Algorithm 22 Partially Corrupt Node

```
1: function CORRUPT
2:   Upon receiving (“Corrupt”, Corrupt-Code) from Adv:
3:   if type=’full’ then
4:     Replace code of  $\mathcal{F}_{Node}$  with code of Fully Corrupted  $\mathcal{F}_{Node}$ 
5:   end if
6: end function
7: function ATTACH
8:   Upon receiving (Sender, “Attach”, volume-id) from  $\mathcal{F}_{SMT}$ :
9:   if Source is  $\mathcal{F}_{Compute}$  then
10:    if attached-volume is None then
11:      Set attached-volume to volume-id
12:      Send- $\mathcal{F}_{SMT}$  ( $\mathcal{F}_{Node}$ ,  $\mathcal{F}_{Compute}$ , “Attach Volume”, session-id, Success);
13:    else
14:      Send- $\mathcal{F}_{SMT}$  ( $\mathcal{F}_{Node}$ ,  $\mathcal{F}_{Compute}$ , “Detach Volume”, session-id, Fail);
15:    end if
16:  else
17:    drop message
18:  end if
19: end function
20:
21: function DETACH
22:   Upon receiving (Sender, “Detach”, volume-id) from  $\mathcal{F}_{SMT}$ :
23:   if Source is  $\mathcal{F}_{Compute}$  then
24:    if attached-volume is volume-id then
25:      Set attached-volume to None
26:      Send- $\mathcal{F}_{SMT}$  ( $\mathcal{F}_{Node}$ ,  $\mathcal{F}_{Compute}$ , “Detach Volume”, session-id, Success);
27:    else
28:      Send- $\mathcal{F}_{SMT}$  ( $\mathcal{F}_{Node}$ ,  $\mathcal{F}_{Compute}$ , “Detach Volume”, session-id, Fail);
29:    end if
30:  else
31:    drop message
32:  end if
33: end function
```

```

34:
35: function EXECUTEREQUEST
36:   Upon receiving ( $\mathcal{F}_{Compute}$ , “Execute Access Node”, session-id, user-id, node-id, AccessRe-
    quest) from  $\mathcal{F}_{SMT}$ :
37:   if session-id=(U,N) where N non-repetitive for user U and U is the owner of the node then
38:     if AccessRequest requires data then
39:       StoreBuffer( $\mathcal{F}_{Node}$ ,  $\mathcal{F}_{Volume}$ , “Access”, operation specified by AccessRequest, session-
        id, user-id, node-id)
40:       Send ( $\mathcal{F}_{Node}$ ,  $\mathcal{F}_{Volume}$ , “Access”, operation specified by AccessRequest, session-id,
        user-id, node-id)
41:       Upon receiving ( $\mathcal{F}_{Volume}$ ,  $\mathcal{F}_{Node}$ , “Success”, data, session-id) from  $\mathcal{F}_{SMT}$ :
42:         Store returned data
43:       end if
44:       results  $\leftarrow$  EXECUTE(AccessRequest);
45:       Send (Adversary,  $\mathcal{F}_{Node}$ ,  $\mathcal{F}_{Volume}$ , “Access”, operation specified by AccessRequest,
        session-id, user-id, node-id, results, successful)
46:       Send- $\mathcal{F}_{SMT}$  ( $\mathcal{F}_{Node}$ ,  $\mathcal{F}_{Compute}$ , “Node Accessed”, session-id, results, Successful);
47:     else
48:       Send (Adversary,  $\mathcal{F}_{Node}$ ,  $\mathcal{F}_{Volume}$ , “Access”, operation specified by AccessRequest,
        session-id, user-id, node-id, failure)
49:       Send- $\mathcal{F}_{SMT}$  ( $\mathcal{F}_{Node}$ ,  $\mathcal{F}_{Compute}$ , “Node Accessed”, session-id, None, Fail);
50:     end if
51: end function

```

Algorithm 23 Fully Corrupt Node

```

1: function RECEIVEMESSAGE
2:   Upon receiving (Source, message) from  $\mathcal{F}_{SMT} \setminus \mathcal{F}_{ExtNet}$ :
3:   Send- $\mathcal{F}_{SMT}$  (source, Adversary, message);
4: end function
5: function SENDMESSAGE
6:   Upon receiving (Adversary, “Forward”, message, destination) from  $\mathcal{F}_{SMT}$ :
7:   Send- $\mathcal{F}_{SMT}$  ( $\mathcal{F}_{Node}$ , destination, message);
8: end function
9:
10: function MAIN
11:   Upon receiving a message which does not contain “Forward” & Source=Adversary from
     $\mathcal{F}_{SMT}$ :
12:   Apply the request;
13:   Send- $\mathcal{F}_{SMT}$  ( $\mathcal{F}_{Compute}$ , Adversary, result of the request);
14: end function

```

Algorithm 24 Identity

```
1: function CORRUPT
2:   Upon receiving (“Corrupt”, Corrupt-Code) from Adv:
3:   Replace code of  $\mathcal{F}_{Identity}$  with code of Corrupted  $\mathcal{F}_{Identity}$ 
4: end function
5: function SERVICEVALIDATION
6:   Upon receiving (Receiver, “Service Validation”, session-id,  $creds_{service}$ ,  $creds$ , Request) from
    $\mathcal{F}_{SMT}$ :
7:   if  $creds_{service}$  &  $creds$  are valid &  $creds$  is allowed to perform the Request then
8:     valid=True;
9:   else
10:    valid=False;
11:   end if
12:   Send- $\mathcal{F}_{SMT}$  ( $\mathcal{F}_{Identity}$ , Receiver, “Service Validated”, session-id, user-id, service-id, Request,
   valid);
13: end function
```

Algorithm 25 Corrupt Identity

```
1: function RECEIVEMESSAGE
2:   Upon receiving (Source, message) from  $\mathcal{F}_{SMT} \setminus \mathcal{F}_{ExtNet}$ :
3:   Send- $\mathcal{F}_{SMT}$  (source, Adversary, message);
4: end function
5: function SENDMESSAGE
6:   Upon receiving (Adversary, “Forward”, message, destination) from  $\mathcal{F}_{SMT}$ :
7:   Send- $\mathcal{F}_{SMT}$  ( $\mathcal{F}_{Identity}$ , destination, message);
8: end function
9:
10: function MAIN
11:   Upon receiving a message which does not contain “Forward” & Source=Adversary from
    $\mathcal{F}_{SMT}$ :
12:   Apply the request;
13:   Send- $\mathcal{F}_{SMT}$  ( $\mathcal{F}_{Compute}$ , Adversary, result of the request);
14: end function
```

4.3 Simulator for Ideal Cloud Using Bearer Tokens

We show the complete simulator S for the ideal cloud using bearer tokens in Algorithm 26⁴. Here, the simulator gets input from ideal cloud and environment E and based on the conditions it either response to or convert them into intermediate messages and sends them to the desired destination. S buffers received information from the ideal cloud to make future decisions and keep the state of each request.

In the OpenStack Services world, whenever a service is corrupted, the adversary gets access to the information that are stored in the services database such as user credentials which have unfinalized request or have made a new request. This situation should also be correct in the ideal Cloud/Simulator world. Therefore, in the case of corruption, the cloud sends some extra information such as list of affected user-id to S . The simulator then creates and stores credential per each user-id and use it as needed in the following messages.

Note that, since the bearer token is an unscoped multi usage token, the adversary is able to make different requests on behalf of the compromised user. Also, she is able to send the same request more than once to another service. To realize these properties, the simulator only checks the credential and hands the request message to the cloud and responses based on the results it receives from the cloud.

4.4 Analysis

Here, we demonstrate that the ideal cloud UC-emulates the OpenStack Services. As with most UC analyses, our argument proceeds via induction on the steps taken by the environment E . We show that for any message that E might send, the next incoming message received by E maintains the invariant that *E 's view in the ideal cloud and OpenStack Services is identical*. More specifically, for any state that E can reach, the action of the simulator S up to that point must have ensured that E 's view is the same in both worlds. Ergo, E cannot distinguish whether it is interacting with the OpenStack Services or with the composition of ideal cloud and the simulator.

To improve the presentation of this proof, we make the argument in stages. We begin with a ‘warmup’ analysis (property 1) that makes two simplifying assumptions: (i) E permits each OpenStack command to complete before executing the next one and (ii) E has not compromised any OpenStack services. We then remove those assumptions in pieces. The operation of the ideal cloud and OpenStack Services can change when E is permitted to interleave commands, yet fortunately both clouds change in identical ways (property 2). Finally, permitting E to compromise services causes yet more changes to the behavior, and does so in a manner that depends on how the token mechanism works, yet once again our invariant is maintained (property 3). Looking ahead, in Sections 5 and 6 we will introduce an improved ‘one-time’ token mechanism and analyze its security. As a result, we purposely provide our proof of property 3 in a manner that can be partially re-used when considering other token mechanisms.

In our attempt to balance comprehensiveness with comprehension, we explain each property for only one combination of the ideal cloud commands (attach/detach volume, access node, create node, or get image) and with a focus only on those OpenStack services most pertinent to the command. We believe that our choices are ‘representative’ of the properties we wish to demonstrate, in the sense that they showcase all of the insights involved in the analysis without subjecting the reader to redundant case analyses for the remaining commands and services.

⁴The description of notation used in the algorithm is provided in appendix A

Algorithm 26 Simulator with corrupted services for bearer token

```
1: function SIMULATOR(message)
2:   Upon receiving ("Corrupt", Service, value, corrupt-code) from Env:
3:   Corrupt[Service]=value;
4:   if FindServiceCorrupt(Service, Service-id,  $creds_{service}$ ) &  $creds_{service}$  =NULL then
5:     Credential= Generate credential for the service;
6:      $creds_{service}$  =Credential;
7:     UpdateServiceCorrupt(Service, Service-id,  $creds_{service}$ );
8:   end if
9:   Send-IdealCloud("Corrupt", Service,value);
10:
11:   Upon receiving (DB of (image-id, corresponding-Image),List of (user-id)) from Ideal Cloud:
12:   StoreDB (All (image-id, corresponding-Image));
13:   Create unique Credential per each user-id in the List if it has not been created before;
14:   StoreBufferUserCorrupt(user-id,Credential);
15:
16:   Upon receiving DB of (user-id, roles))from Ideal Cloud:
17:   Create unique Credential per each user-id in the List if it has not been created before;
18:   StoreBufferUserCorrupt(user-id,Credential, roles);
19:
20:   Upon receiving List of (user-id)from Ideal Cloud:
21:   Create unique Credential per each user-id in the List if it has not been created before;
22:   storeBufferUserCorrupt(user-id,Credential);
23:
24:   Upon receiving (Sender, Receiver, message) from Env:
25:   if Receiver= $\mathcal{F}_{Compute}$  & Corrupt[Compute]="Active" then
26:     Send-Env(Sender, Adversary, message);
27:   else if Receiver= $\mathcal{F}_{Identity}$  & Corrupt[Identity]="Active" then
28:     Send-Env(Sender, Adversary, message);
29:   else if Receiver= $\mathcal{F}_{Image}$  & Corrupt[Image]="Active" then
30:     Send-Env(Sender, Adversary, message);
31:   else if Receiver= $\mathcal{F}_{BlockStorage}$  & Corrupt[Storage]="Active" then
32:     Send-Env(Sender, Adversary, message);
33:   else if Receiver= $\mathcal{F}_{Node}$ node-id & Corrupt[Node node-id ]="Active" then
34:     Send-Env(Sender, Adversary, message);
35:   else if Receiver= $\mathcal{F}_{Volume}$  volume-id & Corrupt[Volume volume-id ]="Active" then
36:     Send-Env(Sender, Adversary, message);
37:   end if
38:
```

39:

40: Upon receiving (Receiver, "Node Access", session-id, user-id, node-id, RequestActivity)
 from Cloud:

41: StoreBuffer(Receiver, "Node Access", session-id, user-id, node-id, RequestActivity)

42: Send-Env ($\mathcal{F}_{Compute}$, "Node Access", session-id, user-id, node-id, RequestActivity)

43:

44: Upon receiving ("Access Node", session-id, user-id, node-id, result, valid)

45: StoreBuffer("Access Node", session-id, user-id, node-id, result, valid)

46: Send-Env ($\mathcal{F}_{Compute}$, "Access Node", session-id, user-id, node-id, result, valid)

47:

48: Upon receiving (Adversary, $\mathcal{F}_{Compute}$, "Access Node", session-id, node-id, RequestActivity)
 from Env:

49: Send-IdealCloud(Adversary, "Access Node", session-id, node-id, RequestActivity)

50:

51: Upon Receiving ("Access Node", session-id, node-id, RequestActivity, results) from Ideal-
 Cloud

52: Send-Env("Access Node", session-id, node-id, RequestActivity, results);

53:

54: Upon receiving (Receiver, "Attach Volume", session-id, user-id, node-id) from Cloud:

55: StoreBuffer(Receiver, "Attach Volume", session-id, user-id, node-id)

56: Send-Env ($\mathcal{F}_{Compute}$, "Attach Volume", session-id, user-id, node-id)

57:

58: Upon Receiving("Attach Volume", session-id, volume-id, node-id, success)

59: StoreBuffer("Attach Volume", session-id, volume-id, node-id, success)

60: Send-Env ($\mathcal{F}_{Compute}$, "Attach Volume", session-id, volume-id, node-id, success)

61:

62: Upon Receiving("Attach Volume", session-id, volume-id, node-id, failure)

63: StoreBuffer("Attach Volume", session-id, volume-id, node-id, failure)

64: Send-Env ($\mathcal{F}_{Compute}$, "Attach Volume", session-id, volume-id, node-id, failure)

65:

66: Upon Receiving("Attach Volume", session-id, volume-id, node-id, valid)

67: StoreBuffer("Attach Volume", session-id, volume-id, node-id, valid)

68: Send-Env ($\mathcal{F}_{Identity}$, "Attach Volume", session-id, volume-id, node-id, valid)

69:

70: Upon receiving (Adversary, $\mathcal{F}_{Compute}$, "Attach Volume", session-id, node-id, RequestActiv-
 ity) from Env:

71: Send-IdealCloud(Adversary, "Attach Volume", session-id, node-id, RequestActivity);

72:

```

73:
74:   Upon Receiving ("Attach Volume", session-id, volume-id, node-id)
75:   if (Compute is Corrupt OR Node node-id is Corrupt) AND (Storage is Corrupt OR Volume
volume-id is Corrupt) then
76:     Send-Env("Attach Volume", session-id, volume-id, node-id, success)
77:   else
78:     Send-Env("Attach Volume", session-id, volume-id, node-id, failure)
79:   end if
80:
81:   Upon receiving (Receiver, "Detach Volume", session-id, user-id, node-id) from Cloud:
82:   StoreBuffer(Receiver, "Detach Volume", session-id, user-id, node-id)
83:   Send-Env ( $\mathcal{F}_{Compute}$ , "Detach Volume", session-id, user-id, node-id)
84:
85:   Upon Receiving("Detach Volume", session-id, volume-id, node-id, success)
86:   StoreBuffer("Detach Volume", session-id, volume-id, node-id, success)
87:   Send-Env ( $\mathcal{F}_{Compute}$ , "Detach Volume", session-id, volume-id, node-id, success)
88:
89:   Upon Receiving("Detach Volume", session-id, volume-id, node-id, failure)
90:   StoreBuffer("Detach Volume", session-id, volume-id, node-id, failure)
91:   Send-Env ( $\mathcal{F}_{Compute}$ , "Detach Volume", session-id, volume-id, node-id, failure)
92:
93:   Upon Receiving("Detach Volume", session-id, volume-id, node-id, valid)
94:   StoreBuffer("Detach Volume", session-id, volume-id, node-id, valid)
95:   Send-Env ( $\mathcal{F}_{Identity}$ , "Detach Volume", session-id, volume-id, node-id, valid)
96:
97:   Upon receiving (Adversary,  $\mathcal{F}_{Compute}$ , "Detach Volume", session-id, node-id, RequestActiv-
ity) from Env:
98:   Send-IdealCloud(Adversary, "Detach Volume", session-id, node-id, RequestActivity)
99:
100:  Upon Receiving ("Detach Volume", session-id, volume-id, node-id)
101:  if (Compute is Corrupt OR Node node-id is Corrupt) OR (Storage is Corrupt OR Volume
volume-id is Corrupt) then
102:    Send-Env("Detach Volume", session-id, volume-id, node-id, success)
103:  else
104:    Send-Env("Detach Volume", session-id, volume-id, node-id, failure)
105:  end if
106:

```

```

107:
108:    $C_2$ – Upon receiving (Receiver, "Create Node", session-id, user-id, image-id, Node-
      Structure) from Ideal Cloud:
109:   StoreBuffer(Receiver,"Create Node", session-id, user-id, image-id, Node-Structure);
110:   Send-Env(Receiver,  $\mathcal{F}_{Compute}$ , "Create Node", session-id, user-id, image-id, Node-
      Structure);
111:
112:   Upon receiving ("validation",user-id, session-id, Request, valid) from IdealCloud:
113:   if FindBuffer("Result, Service, destination, message) with request-ID=session-id then
114:     UpdateBuffer({"Result",  $F_{Service}$ , destination, message}, {Receiver=destination,
      Sender=  $F_{Service}$ , "Service validated", session-id, Request, valid});
115:     Send-Env(Receiver, Sender, "Service validated", Request, valid);
116:   end if
117:
118:    $AC_1$ – Upon receiving (Adversary,  $\mathcal{F}_{Compute}$ , request) from Env:
119:   if Corrupt[Compute]="Active" then
120:     Send-IdealCloud("MainComputeCorrupt", request);
121:   end if
122:
123:    $C_3C_1I_3$ – Upon receiving ("Get Image", session-id, Corresponding-Image, valid) from Ide-
      alCloud:
124:   if FindBuffer("Result, Service, destination, message) with request-ID=session-id then
125:     UpdateBuffer({"Result",  $F_{Service}$ , destination, message}, { $\mathcal{F}_{Image}$ ,  $\mathcal{F}_{Compute}$ , "Get Im-
      age", session-id, image-id, Corresponding-Image, valid});
126:     StoreDB(image-id, Corresponding-Image);% if this image is not stored in the Sim DB,
      then store it.
127:     Send-Env( $\mathcal{F}_{Image}$ ,  $\mathcal{F}_{Identity}$ , "Service Validation", session-id FImage-id, user-id, "Get
      Image image-id ");
128:   end if
129:
130:    $C_3I_2$ –Upon receiving (Receiver, "Create Node", session-id, user-id, "Corrupted Get Im-
      age") from Ideal Cloud:
131:   StoreBuffer(Receiver, "Service Validation", session-id, user-id, image-id, "Corrupted Get
      Image");
132:   Send-Env( $\mathcal{F}_{Compute}$ ,  $\mathcal{F}_{Identity}$ , "Service Validation", session-id, Compute-id, user-id, "Create
      Node");
133:
134:    $C_3ID_9$ – Upon receiving ("Get Image", session-id, image-id, Corresponding-Image) from
      Ideal Cloud:
135:   if Corrupt[Identity]="Active" & FindBuffer(Receiver,"Create Node Get Image result",
      session-id, user-id, image-id, Node-Structure, Image-valid) then
136:     if Corresponding-Image=NULL then
137:       valid=0;
138:     else
139:       valid=1;
140:     end if
141:

```

```

142:     UpdateBuffer({Receiver,"Create Node Get Image result", session-id, user-id, image-id,
Node-Structure, Image-valid},{Receiver,"Create Node Get Image continue", session-id, user-id,
image-id, Node-Structure, Corresponding-Image, valid});
143:     Send-Env( $\mathcal{F}_{Image}$ ,  $\mathcal{F}_{Compute}$ , "Image", session-id, image-id, , Corresponding-Image);
144:     end if
145:
146:      $C_3I_{10}$ –Upon receiving ("Create Node Continue", session-id, user-id, valid) from Ideal-
Cloud:
147:     if FindBuffer(Receiver, "Node ID continue", session-id, node-id) then
148:         UpdateBuffer({Receiver, "Node ID continue", session-id },{Receiver, "Create Node
Output", session-id })
149:         Send-Env( $\mathcal{F}_{Compute}$ , Receiver, "Node Created", session-id, node-id, valid);%GOTO
 $C_3I_{11}$ 
150:     else if Corrupt[Identity]="Active" & FindBuffer(Receiver,"Create Node node ID", session-
id, user-id, image-id, Node-Structure, Corresponding-Image, valid,node-id) then
151:         UpdateBuffer ({Receiver,"Create Node node ID", session-id, user-id, image-id, Node-
Structure, Corresponding-Image, valid,node-id },{Receiver, "Create Node Output", session-id
});
152:         Send-Env( $\mathcal{F}_{Compute}$ , Receiver, "Node Created", session-id, node-id, valid);%GOTO
 $C_3I_{11}$ 
153:     end if
154:
155:      $C_{12}I, C_3I_8, C_3ID_{11}$ – Upon receiving (Adversary,  $\mathcal{F}_{Compute}$ , "Node ID", session-id, node-id)
from Env:
156:     if Corrupt[Image]="Active" & FindBuffer (Receiver, "Node ID", session-id, user-id, image-
id, "Corrupted Get Image", Corresponding-Image) then
157:         UpdateBuffer({Receiver, "Node ID", session-id, user-id, image-id, "Corrupted Get Im-
age", Corresponding-Image},{Receiver, "Node ID continue", session-id, node-id });
158:          $C_3ID_8$ – Send-IdealCloud (Receiver, "Node ID", session-id, user-id, image-id, "Cor-
rupted Get Image", Corresponding-Image, node-id);
159:     else if Corrupt[Identity]="Active" & FindBuffer(Receiver,"Create Node get node ID",
session-id, user-id, image-id, Node-Structure, Corresponding-Image, valid) then
160:         UpdateBuffer({Receiver,"Create Node get node ID", session-id, user-id, image-id, Node-
Structure, Corresponding-Image, valid},{Receiver,"Create Node node ID", session-id, user-id,
image-id, Node-Structure, Corresponding-Image, valid,node-id })
161:          $C_3ID_{11}$ –Send-IdealCloud("Node ID", session-id, node-id, Corresponding-Image);
162:     else if FindBuffer(Receiver, "Request Node ID", session-id) then
163:         UpdateBuffer ({Receiver, "Request Node ID", session-id },{Receiver, "Node ID con-
tinue", session-id, node-id })
164:         Send-IdealCloud ("Node ID", session-id, node-id);
165:     end if
166:

```

```

167:
168:   Upon receiving (Adversary, Receiver, "Forward", message, destination) from Env:
169:   if Receiver= $\mathcal{F}_{Compute}$  & Corrupt[Compute]="Active" then
170:     if Destination is not a service then
171:       StoreBuffer("Output",  $\mathcal{F}_{Compute}$ , destination, message);
172:     else
173:       StoreBuffer( $\mathcal{F}_{Compute}$ , destination, message);
174:     end if
175:      $C_3C_1$ – Send-Env( $\mathcal{F}_{Compute}$ , destination, message);% TO FOLLOW  $C_3C_1$  (OUTPUT
GOTO  $C_3C_1O_1$ , ELSE GOTO  $C_3C_1ID_1$  [identity] OR  $C_3C_1I_1$  [glance])
176:     else if Receiver= $\mathcal{F}_{Identity}$  & Corrupt[Identity]="Active" then
177:       if destination= $\mathcal{F}_{Compute}$  & Request="Delete Node" & message is "Service Validated"
type & FindBuffer(Receiver,"Corrupt Validated Delete Node", session-id, user-id, node-id)
then
178:         extract the valid value from the message;
179:         UpdateBuffer({Receiver,"Corrupt Validated Delete Node", session-id, user-id, node-
id }, {Receiver,"Corrupt Result Delete Node", session-id, user-id, node-id, valid});
180:          $D_3ID_2$ – Send-Env( $\mathcal{F}_{Identity}$ , destination, message);
181:         else if destination= $\mathcal{F}_{Compute}$  & Request="Create Node with Node-Structure" & mes-
sage is "Service Validated" type & FindBuffer(Receiver,"Create Node validated", session-id,
user-id, image-id, Node-Structure) then
182:           extract the valid value from the message;
183:           UpdateBuffer({Receiver,"Create Node validated", session-id, user-id, image-id,
Node-Structure}, {Receiver,"Create Node result", session-id, user-id, image-id, Node-Structure,
valid});
184:            $C_3ID_2$ – Send-Env( $\mathcal{F}_{Identity}$ , destination, message);
185:           else if destination= $\mathcal{F}_{Image}$  & Request="Get Image image-id " & message is "Service
Validated" type & FindBuffer(Receiver,"Create Node Get Image validated", session-id, user-id,
image-id, Node-Structure, valid) then
186:             extract the Image-valid value from the message;
187:             UpdateBuffer({Receiver,"Create Node Get Image validated", session-id, user-id,
image-id, Node-Structure, valid}, {Receiver,"Create Node Get Image result", session-id, user-
id, image-id, Node-Structure, Image-valid});
188:              $C_3ID_6$ – Send-Env( $\mathcal{F}_{Identity}$ , destination, message);
189:           else
190:             StoreBuffer( $\mathcal{F}_{Identity}$ , destination, message);
191:             Send-Env( $\mathcal{F}_{Identity}$ , destination, message);
192:           end if
193:         else if Receiver= $\mathcal{F}_{Image}$  & Corrupt[Image]="Active" then

```

```

194:     if destination=  $\mathcal{F}_{Compute}$  & message=("Image", session-id, image-id, Corresponding-
      Image ) & FindBuffer(Receiver, "Get Image Result", session-id, user-id, image-id, "Corrupted
      Get Image") where the message session-ID=session-id then
195:         UpdateBuffer ({Receiver, "Get Image Result", session-id, user-id, image-id, "Cor-
      rupted Get Image"}, {Receiver, "Get Node ID", session-id, user-id, image-id, "Corrupted Get
      Image", Corresponding-Image});
196:     else
197:         StoreBuffer( $\mathcal{F}_{Image}$ , destination, message);
198:     end if
199:      $C_3I_6$ – Send-Env( $\mathcal{F}_{Image}$ , destination, message);%GOTO  $C_3I_7ID_1$  [IDENTITY] OR
       $C_3I_7$  [COMPUTE]
200:     end if
201:
202:      $C_3I_6^*$ – Upon receiving (Adversary,  $\mathcal{F}_{Image}$ , "Get Image", image-id) from Env:
203:     if Corrupt[Image]="Active" then
204:         if image-id exist then
205:             Corresponding-Image= extract the corresponding image for image-id;
206:         else
207:             Corresponding-Image= NULL;
208:         end if
209:         Send-Env ( $\mathcal{F}_{Image}$ , Adversary, "Image", image-id, Corresponding-Image );
210:     end if
211:
212:      $D_2$ – Upon receiving (Receiver, "Delete Node", session-id, user-id, node-id) from Ideal
      cloud:
213:     StoreBuffer(Receiver,"Delete Node", session-id, user-id, node-id);
214:     Send-Env(Receiver,  $\mathcal{F}_{Compute}$ , "Delete Node", session-id, node-id, user-id);
215:
216:      $AC_3$ – Upon receiving ("MainComputeCorruptResult", result) from IdealCloud:
217:     Send-Env ( $\mathcal{F}_{Compute}$ , Adversary, result); % GOTO  $C_3C_1$  (for forwarding), GOTO  $AC_1$  (for
      Adv to make new request)
218:
219:      $D_3ID_5$ – Upon receiving (Receiver, "Delete Node Completed", session-id, user-id, node-id,
      valid, NodeExist) from Ideal Cloud:
220:     StoreBuffer(Receiver, "Delete Node Completed", session-id, user-id, node-id, valid, Node-
      Exist);
221:     if valid=1 & NodeExist=1 then
222:         Send-Env( $\mathcal{F}_{Compute}$ , Receiver, "Delete Node", session-id, node-id, successful );
223:     else
224:         Send-Env( $\mathcal{F}_{Compute}$ , Receiver, "Delete Node", session-id, node-id, Fail );
225:     end if
226:

```

```

227:
228:   Upon receiving ("Confirm", session-id) from Env:
229:   if FindBuffer(Receiver,"Create Node", session-id, user-id, image-id, Node-Structure) then
230:     if Corrupt[Compute]="Active" then
231:       if FindBufferUserCorrupt(user-id, Credential) then
232:         creds =Credential;
233:       else
234:         Credential= Generate credential for the user;
235:         creds = Credential;
236:         StoreBufferUserCorrupt(user-id,Credential);
237:       end if
238:        $C_3C$ – Send-Env(Receiver, Adversary, "Create Node", session-id, creds, image-id,
Node-Structure);% GOTO  $AC_1$  (Adv makes a new request),  $C_3C_1$  (for forwarding)
239:       else if Corrupt[Identity]="Active" then
240:         UpdateBuffer({Receiver,"Create Node", session-id, user-id, image-id, Node-
Structure},{Receiver,"Create Node validation", session-id, user-id, image-id, Node-Structure});
241:         Request="Create Node with Node-Structure";
242:          $C_3ID$ – Send-Env( $\mathcal{F}_{Compute}$ ,  $\mathcal{F}_{Identity}$ , "Service Validation", session-id, Service-id,
user-id, Request);
243:       else if Corrupt[Image]="Active" then
244:          $C_3I$ – Send-IdealCloud("Confirm", session-id);
245:       else
246:          $C_3$ – Send-IdealCloud("Confirm", session-id);
247:       end if
248:       else if FindBuffer(Receiver,"Create Node validation", session-id, user-id, image-id, Node-
Structure) then
249:         if Corrupt[Identity]="Active" then
250:           if FindBufferUserCorrupt(user-id, Credential,roles) then
251:             creds =Credential;
252:           else
253:             Credential= Generate credential for the user;
254:             creds = Credential;
255:             StoreBufferUserCorrupt(user-id,Credential,roles);
256:           end if
257:           Extract  $creds_{service}$  from ServiceCorrupt(Service, Service-id,  $creds_{service}$ ) where
Service= $\mathcal{F}_{Compute}$ ;
258:           UpdateBuffer({Receiver,"Create Node validation", session-id, user-id, image-id,
Node-Structure},{Receiver,"Create Node validated", session-id, user-id, image-id, Node-
Structure});
259:            $C_3ID_1$ – Send-Env ( $\mathcal{F}_{Compute}$ , Adversary, "Service validation, session-id,  $creds_{service}$ ,
creds, Request); % GOTO  $D_3ID_2$  OR ADV MAY SEND ARBITRARY MESSAGE TO A
SERVICE
260:         end if
261:       else if FindBuffer(Receiver,"Create Node result", session-id, user-id, image-id, Node-
Structure, valid) then

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262:         if Corrupt[Identity]="Active" then
263:             if valid=0 then
264:                 UpdateBuffer({Receiver,"Create Node result", session-id, user-id, image-id,
Node-Structure, valid},{Receiver,"Create Node result continue", session-id, user-id, image-id,
Node-Structure, valid});
265:                  $C_3ID_3^*$ – Send-Env( $\mathcal{F}_{Compute}$ , Receiver, "Create Node", session-id, NULL,
Fail);%GOTO  $C_3ID_4^*$ 
266:             else
267:                 UpdateBuffer({Receiver,"Create Node result", session-id, user-id, image-id,
Node-Structure, valid},{Receiver,"Create Node Get Image", session-id, user-id, image-id, Node-
Structure, valid});
268:                  $C_3ID_3^*$ – Send-Env( $\mathcal{F}_{Compute}$ ,  $\mathcal{F}_{Image}$ , "Get Image", session-id, user-id, image-
id);%GOTO  $C_3ID_4^*$ 
269:             end if
270:         end if
271:         else if FindBuffer(Receiver,"Create Node result continue", session-id, user-id, image-id,
Node-Structure, valid) then
272:              $C_3ID_4^*$ – Send-IdealCloud("Create Node Output valid", session-id, Fail);
273:         else if FindBuffer(Receiver,"Create Node Get Image", session-id, user-id, image-id, Node-
Structure, valid) then
274:             UpdateBuffer({Receiver,"Create Node Get Image", session-id, user-id, image-id, Node-
Structure, valid},{Receiver,"Create Node Get Image validation", session-id, user-id, image-id,
Node-Structure, valid});
275:              $C_3ID_4^*$ – Send-Env( $\mathcal{F}_{Image}$ ,  $\mathcal{F}_{Identity}$ , "Service Validation", session-id, compute-id, user-
id, Request="Get Image image-id ");
276:         else if FindBuffer(Receiver,"Create Node Get Image validation", session-id, user-id, image-
id, Node-Structure, valid) then
277:             if Corrupt[Identity]="Active" then
278:                 if FindBufferUserCorrupt(user-id, Credential,roles) then
279:                     creds =Credential;
280:                 else
281:                     Credential= Generate credential for the user;
282:                     creds = Credential;
283:                     StoreBufferUserCorrupt(user-id,Credential,roles);
284:                 end if
285:                 Extract credsservice from ServiceCorrupt(Service, Service-id, credsservice) where
Service= $\mathcal{F}_{Image}$ ;
286:                 UpdateBuffer({Receiver,"Create Node Get Image validation", session-id, user-id,
image-id, Node-Structure, valid},{Receiver,"Create Node Get Image validated", session-id,
user-id, image-id, Node-Structure, valid});
287:                  $C_3ID_5^*$ – Send-Env ( $\mathcal{F}_{Image}$ , Adversary, "Service validation, session-id, credsservice,
creds, Request="Get Image image-id ");
288:             end if

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289:   else if FindBuffer(Receiver,"Create Node Get Image result", session-id, user-id, image-id,
Node-Structure, Image-valid) then
290:       if Corrupt[Identity]="Active" then
291:           if Image-valid=0 then
292:               UpdateBuffer({Receiver,"Create Node Get Image result", session-id, user-id,
image-id, Node-Structure, Image-valid}, {Receiver,"Create Node result continue", session-id,
user-id, image-id, Node-Structure, Fail});
293:                $C_3ID_7$ – Send-Env( $\mathcal{F}_{Compute}$ , Receiver, "Create Node", session-id, NULL,
Fail);%GOTO  $C_3ID_4^*$ 
294:           else
295:               UpdateBuffer({Receiver,"Create Node Get Image result", session-id, user-id,
image-id, Node-Structure, Image-valid},{Receiver,"Create Node Get Image result", session-id,
user-id, image-id, Node-Structure, Image-valid})
296:                $C_3ID_7$ – Send-IdealCloud("Get Image", session-id, image-id);%GOTO  $C_3ID_8$ 
297:           end if
298:       end if
299:   else if FindBuffer(Receiver,"Create Node Get Image continue", session-id, user-id, image-
id, Node-Structure, Corresponding-Image, valid) then
300:       if Corrupt[Identity]="Active" & valid=0 then
301:           UpdateBuffer({Receiver,"Create Node Get Image continue", session-id, user-id,
image-id, Node-Structure, Corresponding-Image, valid}, {Receiver,"Create Node result con-
tinue", session-id, user-id, image-id, Node-Structure, Fail});
302:            $C_3ID_{10}$ – Send-Env( $\mathcal{F}_{Compute}$ , Receiver, "Create Node", session-id, NULL,
Fail);%GOTO  $C_3ID_4^*$ 
303:       else if Corrupt[Identity]="Active" & valid=1 then
304:           UpdateBuffer({Receiver,"Create Node Get Image continue", session-id, user-id,
image-id, Node-Structure, Corresponding-Image, valid}, {Receiver,"Create Node get node ID",
session-id, user-id, image-id, Node-Structure, Corresponding-Image, valid});
305:            $C_3ID_{10}$ – Send-Env( $\mathcal{F}_{Compute}$ , Adversary, "Request Node ID", session-id);%GOTO
 $C_3ID_{11}$ 
306:       end if
307:   else if FindBuffer( $\mathcal{F}_{Compute}$ , destination, message) where the request-ID in the message is
equal to session-id then
308:       if destination= $\mathcal{F}_{Identity}$  then
309:           if Corrupt[Identity]!="Active" then
310:               valid=Fail;
311:           if (user-id,creds,roles)  $\in$  BufferUserCorrupt & request in the message  $\in$  roles
then
312:               valid=Successful;
313:           end if
314:           UpdateBuffer({ $\mathcal{F}_{Compute}$ , destination, message}, {Receiver=destination,
Sender=  $F_{Compute}$ , "Service validated", session-id, Request, valid});
315:            $C_3C_1ID_1$ – Send-Env(Receiver, Sender, "Service validated", Request, valid); %
GOTO  $C_3C_1ID_2$ 
316:       else
317:           Send-Env( $\mathcal{F}_{Compute}$ , Adversary, message);
318:       end if

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319:
320:     else if destination= $\mathcal{F}_{Image}$  then
321:         if Corrupt[Image] !="Active" then
322:             if (user-id, creds)  $\in$  BufferUserCorrupt then
323:                 extract user-id from the message;
324:                 Message= message that the user credential is replaced by user-id;
325:                 UpdateBuffer( $\{\mathcal{F}_{Compute}, destination, message\}, \{"Result", \mathcal{F}_{Compute}, destination, message\}$ );
326:                  $C_3C_1I_1$ – Send-IdealCloud(Message);%GOTO  $C_3C_1I_2$ 
327:             else
328:                 UpdateBuffer( $\{\mathcal{F}_{Compute}, destination, message\}, \{\mathcal{F}_{Image}, \mathcal{F}_{Compute}, "Get Image", session-id, image-id, NULL, Fail\}$ );
329:                  $C_3C_1I_1$ – Send-Env( $\mathcal{F}_{Image}, \mathcal{F}_{Identity}, "Service Validation", session-id, FImage-id, user-id, "Get Image image-id "$ );%GOTO  $C_3C_1I_4$ 
330:             end if
331:         else
332:             Send-Env( $\mathcal{F}_{Compute}, Adversary, message$ );
333:         end if
334:     end if
335:     else if FindBuffer(Receiver, Sender, "Service validated", session-id, Request, valid) then
336:         if Sender= $\mathcal{F}_{Compute}$  & Corrupt[Compute]="Active" then
337:              $C_3C_1ID_2$ – Send-Env(Receiver, Adversary, message);
338:         else if Sender= $\mathcal{F}_{Image}$  & Corrupt[Image]="Active" then
339:              $C_3I_7ID_2$ – Send-Env(Receiver, Adversary, message);
340:         end if
341:     else if FindBuffer( $\mathcal{F}_{Image}, destination, message$ ) where the session-ID in the message is equal to session-id then
342:         if destination=  $\mathcal{F}_{Compute}$  & message=("Image", session-id, image-id, Corresponding-Image ) & FindBuffer(Receiver, "Get Image Result", session-id, user-id, image-id, "Corrupted Get Image") where the message request-ID=session-id then
343:             UpdateBuffer( $\{Receiver, "Get Image Result", session-id, user-id, image-id, "Corrupted Get Image"\}, \{Receiver, "Node ID", session-id, user-id, image-id, "Corrupted Get Image", Corresponding-Image\}$ );
344:             RemoveBuffer( $\mathcal{F}_{Image}, destination, message$ );
345:              $C_3I_7$ – Send-Env ( $\mathcal{F}_{Compute}, Adversary, "Request Node ID", session-id$ );
346:         else if destination= $\mathcal{F}_{Identity}$  then
347:             if Corrupt[Identity] !="Active" then
348:                 if FindDBRequest(session-id, Credential, ServiceObject-List, Black-List) where request-ID=session-id & Credential=creds & ( $\mathcal{F}_{Image}, Object$ )  $\in$  ServiceObject-List &  $\mathcal{F}_{Image} \notin$  Black-List then
349:                     AddBlack-Listsession-id( $\mathcal{F}_{Image}$ );
350:                     valid=successful;

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351:
352:         else
353:             valid=fail;
354:         end if
355:         StoreBuffer(Receiver=destination, Sender=  $\mathcal{F}_{Image}$ , "Service validated", session-
            id, Request, valid);
356:          $C_3I_7ID_1$ – Send-Env(Receiver, Sender, "Service validated", Request, valid);
357:         else
358:             Send-Env( $\mathcal{F}_{Image}$ , Adversary, message);
359:         end if
360:     end if
361:     else if FindBuffer( $\mathcal{F}_{Image}$ ,  $\mathcal{F}_{Compute}$ , "Get Image", session-id, image-id, Corresponding-
        Image, valid" ) then
362:         UpdateBuffer({ $\mathcal{F}_{Image}$ ,  $\mathcal{F}_{Compute}$ , "Get Image", session-id, image-id, Corresponding-
            Image, valid"},{ $\mathcal{F}_{Image}$ ,  $\mathcal{F}_{Compute}$ , "validated Get Image", session-id, image-id, Corresponding-
            Image, valid"});
363:          $C_3C_1I_4$ – Send-Env ( $\mathcal{F}_{Identity}$ ,  $\mathcal{F}_{Image}$ , "Service Validated", session-id, user-id, service-id,
            Request="Get Image image-id ", valid);
364:         else if FindBuffer( $\mathcal{F}_{Image}$ ,  $\mathcal{F}_{Compute}$ , "validated Get Image", session-id, image-id,
            Corresponding-Image, valid" ) then
365:             UpdateBuffer({ $\mathcal{F}_{Image}$ ,  $\mathcal{F}_{Compute}$ , "validated Get Image", session-id, image-id,
                Corresponding-Image, valid"}, { $\mathcal{F}_{Image}$ ,  $\mathcal{F}_{Compute}$ , "Result Get Image", session-id, image-id,
                Corresponding-Image, valid"});
366:              $C_3C_1I_5$ – Send-Env( $\mathcal{F}_{Image}$ ,  $\mathcal{F}_{Compute}$ , "Image", session-idimage-id, Corresponding-
                Image);
367:             else if FindBuffer( $\mathcal{F}_{Image}$ ,  $\mathcal{F}_{Compute}$ , "Result Get Image", session-id, image-id,
                Corresponding-Image, valid" ) then
368:                 RemoveBuffer( $\mathcal{F}_{Image}$ ,  $\mathcal{F}_{Compute}$ , "Result Get Image", session-id, image-id,
                    Corresponding-Image, valid");
369:                 if Corrupt[Compute]="Active" then
370:                      $C_3C_1I_6$ – Send-Env( $\mathcal{F}_{Compute}$ , Adversary, message);
371:                 end if
372:             else if FindBuffer("Output", Service, destination, message) then
373:                 RemoveBuffer("Output", Service, destination, message);
374:                 if Service= $\mathcal{F}_{Compute}$  & Corrupt[Compute]="Active" & message contains "Delete Node"
                    then
375:                      $D_3O_1$ – Send-IdealCloud(Receiver, "Delete Node", session-id, node-id, valid);
376:                 else if Service= $\mathcal{F}_{Compute}$  & Corrupt[Compute]="Active" & message contains "Create
                    Node" then
377:                      $C_3C_1O_1$ – Send-IdealCloud(Receiver, "Create Node result", session-id, node-id,
                        valid);
378:                 end if
379:             else if FindBuffer(Receiver, "Service Validation", session-id, user-id, image-id, "Corrupted
                Get Image" ) then
380:                 UpdateBuffer({Receiver, "Service Validation", session-id, user-id, image-id, "Corrupted
                    Get Image"},{Receiver, "Service Validatied", session-id, user-id, image-id, "Corrupted Get
                    Image"})

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381:       $C_3I_3$ – Send-Env( $\mathcal{F}_{Identity}$ ,  $\mathcal{F}_{Compute}$ , "Service Validated", session-id, user-id, Compute-
id, "Create Node", Successful);
382:      else if FindBuffer(Receiver, "Service Validatied", session-id, user-id, image-id, "Corrupted
Get Image") then
383:          UpdateBuffer({Receiver, "Service Validatied", session-id, user-id, image-id, "Corrupted
Get Image"}, {Receiver, "Get Image", session-id, user-id, image-id, "Corrupted Get Image"})
384:           $C_3I_4$ – Send-Env( $\mathcal{F}_{Compute}$ ,  $\mathcal{F}_{Image}$ , "Get Image", session-id, user-id, image-id);
385:      else if FindBuffer(Receiver, "Get Image", session-id, user-id, image-id, "Corrupted Get
Image") then
386:          UpdateBuffer({Receiver, "Get Image", session-id, user-id, image-id, "Corrupted Get
Image"}, {Receiver, "Get Image Result", session-id, user-id, image-id, "Corrupted Get Im-
age"});
387:      if Corrupt[Image]="Active" then
388:          if FindBufferUserCorrupt(user-id, Credential) then
389:              creds =Credential;
390:          else
391:              Credential= Generate credential for the user;
392:              creds =Credential;
393:              StoreBufferUserCorrupt(user-id,Credential);
394:          end if
395:           $C_3I_5$ – Send-Env( $\mathcal{F}_{Image}$ , Adversary, message = ("Get Image", session-id, creds,
image-id));% GOTO  $C_3I_6$  FOR FORWARDING,  $C_3I_6^*$  FOR MAKEING NEW REQUEST
396:      end if
397:      else if FindBuffer(Receiver, "Create Node Output", session-id) then
398:          RemoveBuffer(Receiver, "Create Node Output", session-id);
399:           $C_3I_{11}$ – Send-IdealCloud("Create Node Output", session-id);
400:      else if FindBuffer(Receiver, "Delete Node Completed", session-id, user-id, node-id, valid,
NodeExist) then
401:           $D_3ID_6$ – Send-IdealCloud(Receiver, "Delete Node", session-id, node-id, valid); %GOTO
 $D_3O_2$ 
402:      else if FindBuffer(Receiver,"Delete Node", session-id, user-id, node-id) then
403:          if Corrupt[Compute]="Active" then
404:              if FindBufferUserCorrupt(user-id, Credential) then
405:                  creds =Credential;
406:              else
407:                  Credential= Generate credential for the user;
408:                  creds =Credential;
409:                  StoreBufferUserCorrupt(user-id,Credential);
410:              end if
411:               $D_3C$ – Send-Env(Receiver, Adversary, "Delete Node", session-id, node-id, creds);
412:          else if Corrupt[Identity]="Active" then
413:              UpdateBuffer({Receiver,"Delete Node", session-id, user-id, node-id },
{Receiver,"Corrupt Validation Delete Node", session-id, user-id, node-id });
414:               $D_3ID$ – Send-Env( $\mathcal{F}_{Compute}$ ,  $\mathcal{F}_{Identity}$ , "Service Validation", session-id, Compute-id,
user-id, "Delete Node");
415:          else

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416:          $D_3$ – Send-IdealCloud("Confirm", session-id);
417:     end if
418:     else if FindBuffer(Receiver,"Corrupt Validation Delete Node", session-id, user-id, node-id)
then
419:         if Corrupt[Identity]="Active" then
420:             if FindBufferUserCorrupt(user-id, Credential,roles) then
421:                 creds =Credential;
422:             else
423:                 Credential= Generate credential for the user;
424:                 creds =Credential;
425:                 StoreBufferUserCorrupt(user-id,Credential,roles);
426:             end if
427:             if FindBuffServiceCorrupt(Service-id, Credential) then
428:                 credsservice =Credential;
429:             else
430:                 Credential= Generate credential for the service;
431:                 credsservice =Credential;
432:                 StoreBufferServiceCorrupt(Service-id,Credential);
433:             end if
434:             UpdateBuffer({Receiver,"Corrupt Validation Delete Node", session-id, user-id,
node-id }, {Receiver,"Corrupt Validated Delete Node", session-id, user-id, node-id });
435:              $D_3ID_1$ – Send-Env(Receiver, Adversary, "Service Validation", session-id,
credsservice, creds);
436:         end if
437:         else if FindBuffer(Receiver,"Corrupt Result Delete Node", session-id, user-id, node-id,
valid) then
438:             if Corrupt[Identity]="Active" then
439:                 if valid=0 then
440:                     UpdateBuffer({Receiver,"Corrupt Result Delete Node", session-id, user-id, node-
id, valid}, {Receiver,"Corrupt Output Delete Node", session-id, user-id, node-id, valid});
441:                      $D_3ID_3$ – Send-Env( $\mathcal{F}_{Compute}$ , Receiver, "Delete Node", session-id, node-id,
Fail);% GOTO  $D_3ID_4^*$ 
442:                 else
443:                     RemoveBuffer(Receiver,"Corrupt Result Delete Node", session-id, user-id, node-
id, valid);
444:                      $D_3ID_3$ –Send-IdealCloud("Delete Node", session-id, node-id, valid); %GOTO
 $D_3ID_4$ 
445:                 end if
446:             end if
447:             else if FindBuffer(Receiver,"Corrupt Output Delete Node", session-id, user-id, node-id,
valid) then
448:                  $D_3ID_4^*$ – Send-IdealCloud(Receiver,"Delete Node", session-id, node-id, valid);%GOTO
 $D_3O_2$ 
449:             else if FindBuffer(Receiver, "Node Access", session-id, user-id, node-id, RequestActivity)
then
450:                 Send-IdealCloud("Result Access Node", session-id)
451:             else if FindBuffer(Receiver, "Node Access", session-id, user-id, node-id, result, valid) then
452:                 Send-IdealCloud("Output Access Node", session-id)
453:             else if FindBuffer(Receiver, "Attach Volume", session-id, volume-id, node-id) then

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454:     if Identity is Corrupt then
455:         valid = validity setting used by simulated adversary
456:     else
457:         valid=False
458:     end if
459:     Send-IdealCloud("Confirm Attach Volume", session-id, valid)
460: else if FindBuffer("Attach Volume", session-id, volume-id, node-id, valid) then
461:     Send-IdealCloud("Result Attach Volume", session-id)
462: else if FindBuffer("Attach Volume", session-id, volume-id, node-id, success/fail) then
463:     Send-IdealCloud("Output Attach Volume", session-id)
464: else if FindBuffer(Receiver, "Detach Volume", session-id, volume-id, node-id) then
465:     if Identity is Corrupt then
466:         valid = validity setting used by simulated adversary
467:     else
468:         valid=False
469:     end if
470:     Send-IdealCloud("Confirm Detach Volume", session-id, valid)
471: else if FindBuffer("Detach Volume", session-id, volume-id, node-id, valid) then
472:     Send-IdealCloud("Result Detach Volume", session-id)
473: else if FindBuffer("Detach Volume", session-id, volume-id, node-id, success/fail) then
474:     Send-IdealCloud("Output Detach Volume", session-id)
475: else if FindBuffer(Receiver, "Get Node ID", session-id, user-id, image-id, "Corrupted Get
Image", Corresponding-Image) then
476:     UpdateBuffer({Receiver, "Get Node ID", session-id, user-id, image-id, "Corrupted Get
Image", Corresponding-Image},{Receiver, "Node ID", session-id, user-id, image-id, "Corrupted
Get Image", Corresponding-Image});
477:     Send-Env ( $\mathcal{F}_{Compute}$ , Adversary, "Request Node ID", session-id);
478: else if FindBuffer(Receiver, "Delete Service Validation", session-id, Service-id, user-id,
node-id, valid) then
479:     UpdateBuffer({Receiver, "Delete Service Validation", session-id Service-id, user-id,
node-id, valid},{Receiver, "Delete Service Validated", session-id, Service-id, user-id, node-id,
Valid})
480:      $D_6$ – Send-Env ( $\mathcal{F}_{Identity}$ ,  $\mathcal{F}_{Compute}$ , "Service Validated", session-id, user-id, service-id,
Request, valid);
481: else if FindBuffer(Receiver, "Delete Service Validated", session-id, user-id, node-id, valid)
then
482:     UpdateBuffer({Receiver, "Delete Service Validated", session-id, user-id, node-id,
valid},{Receiver, "Delete Node Continue", session-id, user-id, node-id, valid});
483:      $D_7$ – Send-IdealCloud ("Delete Node Output", session-id, continue);
484: else if FindBuffer(Receiver, "Output Delete Node", session-id) then
485:      $D_{10}$ – Send-IdealCloud("Output Delete Node", session-id);

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486:     else if FindBuffer(Receiver, "Service Validation", session-id, user-id, image-id, "Create
      Node", create-valid, "Get Image", Image-valid, Corresponding-Image) then
487:         UpdateBuffer({Receiver, "Service Validation", session-id, user-id, image-id, "Create
      Node", create-valid, "Get Image", Image-valid, Corresponding-Image},{Receiver, "Service Val-
      idated", session-id, user-id, image-id, Service-id, "Create Node", create-valid, "Get Image",
      Image-valid, Corresponding-Image})
488:          $C_6$ – Send-Env( $\mathcal{F}_{Identity}$ ,  $\mathcal{F}_{Compute}$ , "Service Validated", session-id, user-id, Compute-id,
      "Create Node", create-valid);
489:     else if FindBuffer(Receiver, "Service Validated", session-id, user-id, image-id, Compute-id,
      "Create Node", create-valid, "Get Image", Image-valid, Corresponding-Image) then
490:         if create-valid==successful then
491:             UpdateBuffer({Receiver, "Service Validated", session-id, user-id, image-id,
      Compute-id, "Create Node", create-valid, "Get Image", Image-valid, Corresponding-
      Image},{Receiver, "Get Image Create Node", session-id, user-id, image-id, Compute-id, Image-
      valid, Corresponding-Image})
492:              $C_7I, C_7II$ – Send-Env ( $\mathcal{F}_{Compute}$ ,  $\mathcal{F}_{Image}$ , "Get Image", session-id, user-id, image-id);
493:         else
494:             UpdateBuffer({Receiver, "Service Validated", session-id, user-id, image-id,
      Compute-id, "Create Node", create-valid, "Get Image", Image-valid, Corresponding-
      Image},{Receiver, "Create Node Output", session-id });
495:              $C_7III$ – Send-Env( $\mathcal{F}_{Compute}$ , Receiver, "Node Created", session-id, NULL, Fail);
496:         end if
497:     else if FindBuffer(Receiver, "Get Image Create Node", session-id, user-id, image-id,
      Compute-id, Image-valid, Corresponding-Image) then
498:         UpdateBuffer({Receiver, "Get Image Create Node", session-id, user-id, image-id,
      Compute-id, Image-valid, Corresponding-Image},{Receiver, "Get Image Service Validation",
      session-id, image-id, FImage-id, Image-valid, Corresponding-Image});
499:          $C_8I, C_8II$ – Send-Env( $\mathcal{F}_{Image}$ ,  $\mathcal{F}_{Identity}$ , "Service Validation", session-id, FImage-id,
      user-id, "Get Image Image-id");
500:     else if FindBuffer(Receiver, "Get Image Service Validation", session-id, image-id, FImage-
      id, Image-valid, Corresponding-Image) then
501:         UpdateBuffer({Receiver, "Get Image Service Validation", session-id, user-id, image-id,
      Compute-id, Image-valid, Corresponding-Image},{Receiver, "Get Image Service Validated",
      session-id, image-id, FImage-id, Image-valid, Corresponding-Image})
502:          $C_9I, C_9II$ – Send-Env( $\mathcal{F}_{Identity}$ ,  $\mathcal{F}_{Image}$ , "Service Validated", session-id, user-id, Fimage-
      id, "Get Image image-id", Image-valid);
503:     else if FindBuffer(Receiver, "Get Image Service Validated", session-id, image-id, FImage-
      id, Image-valid, Corresponding-Image) then

```

```

504:     if Image-valid =false then
505:         Corresponding-Image=NULL
506:     end if
507:     UpdateBuffer({Receiver, "Get Image Service Validated", session-id, image-id, FImage-
        id, Image-valid, Corresponding-Image},{Receiver, "Get Image Continue", session-id, image-id,
        Image-valid, Corresponding-Image})
508:      $C_{10I}, C_{10II}$ – Send-Env( $\mathcal{F}_{Image}$ ,  $\mathcal{F}_{Compute}$ , "Image", session-id, image-id,
        Corresponding-Image);
509:     else if FindBuffer(Receiver, "Get Image Continue", session-id, image-id, Image-valid,
        Corresponding-Image) then
510:         if Corresponding-Image= NULL then
511:             UpdateBuffer({Receiver, "Get Image Continue", session-id, image-id, Image-valid,
                Corresponding-Image},{Receiver, "Create Node Output", session-id })
512:              $C_{11II}$ – Send-Env ( $\mathcal{F}_{Compute}$ , Receiver, "Node Created", session-id, NULL, Fail);
513:         else
514:             UpdateBuffer({Receiver, "Get Image Continue", session-id, image-id, Image-valid,
                Corresponding-Image},{Receiver, "Request Node ID", session-id })
515:
516:              $C_{11I}$ – Send-Env( $\mathcal{F}_{Compute}$ , Adversary, "Request Node ID", session-id);
517:         end if
518:     else if FindBuffer(Receiver, "Create Node Output", session-id) then
519:         RemoveBuffer (Receiver, "Create Node Output", session-id);
520:          $C_{8III}, C_{12II}, C_{15I}$ – Send-IdealCloud ("Create Node Output", session-id);
521:     end if
522:
523:      $D_5$ – Upon receiving (Receiver, "Delete Node", session-id, user-id, node-id, valid) from
        Ideal Cloud:
524:     Service-id=Service-id for  $F_{Compute}$ 
525:     StoreBuffer(Receiver, "Delete Service Validation", session-id, Service-id, user-id, node-id,
        valid);
526:     Send-Env( $\mathcal{F}_{Compute}$ ,  $\mathcal{F}_{Identity}$ , "Service Validation", session-id, Compute-id, user-id, "Delete
        node-id ");
527:
528:      $D_9$ – Upon receiving ("Delete Node Completed", session-id, Valid, NodeExist) from Ideal-
        Cloud:
529:     if FindBuffer(Receiver, "Delete Node Continue", session-id, user-id, node-id, valid) then

```

```

530:     UpdateBuffer ({"Delete Node Continue", session-id, user-id, node-id, valid}, {"Output
Delete Node", session-id })
531:     if NodeExist=0 or Valid=0 then
532:         Send-Env ( $\mathcal{F}_{Compute}$ , Receiver, "Delete Node", session-id, node-id, Fail);
533:     else
534:         Send-Env ( $\mathcal{F}_{Compute}$ , Receiver, "Delete Node", session-id, node-id, Successful);
535:     end if
536: end if
537:
538: C5I– Upon receiving (Receiver, "Get Node ID", session-id, user-id, image-id,
Corresponding-Image, Node-Structure) from Ideal Cloud:
539:     StoreBuffer(Receiver, "Service Validation", session-id, user-id, image-id, "Create Node",
Successful, "Get Image", Successful, Corresponding-Image);
540:     Send-Env( $\mathcal{F}_{Compute}$ ,  $\mathcal{F}_{Identity}$ , "Service Validation", session-id, Compute-id, user-id, "Create
Node Node-Structure");% GOTO C6
541:
542: C5II– Upon receiving (Receiver, "Create Node", session-id, user-id, Fail, reason="Get
Image", Node-Structure) from Ideal Cloud:
543:     StoreBuffer(Receiver, "Service Validation", session-id, user-id, "Create Node", Successful,
"Get Image", Fail, NULL);
544:     Send-Env( $\mathcal{F}_{Compute}$ ,  $\mathcal{F}_{Identity}$ , "Service Validation", session-id, Compute-id, user-id, "Create
Node Node-Structure");;% GOTO C6
545:
546: C5III– Upon receiving (Receiver, "Create Node", session-id, user-id, Fail, reason="Create
Node", Node-Structure) from Ideal Cloud:
547:     StoreBuffer(Receiver, "Service Validation", session-id, user-id, "Create Node", Fail, "Get
Image", Fail, NULL);
548:     Send-Env( $\mathcal{F}_{Compute}$ ,  $\mathcal{F}_{Identity}$ , "Service Validation", session-id, Compute-id, user-id, "Create
Node with Node-Structure");;% GOTO C6
549:
550: C14I– Upon receiving ("Create Node Continue", session-id, user-id, valid) from IdealCloud:
551:     if FindBuffer(Receiver, "Node ID continue", session-id, node-id) then
552:         UpdateBuffer({Receiver, "Node ID continue", session-id },{Receiver, "Create Node
Output", session-id })
553:         Send-Env ( $\mathcal{F}_{Compute}$ , Receiver, "Node Created", session-id, node-id, valid);
554:     end if
555: end function

```

In more detail, we show the following three properties:

- **Property 1:** The simulator faithfully emulates the entire workflow required to process one user-provided command, when viewed standalone. We will demonstrate this property by analyzing the simulator’s actions in response to a DeleteNode request; its response to other user actions are more cumbersome but similar in spirit.
- **Property 2:** The simulator faithfully emulates two interleaved user-provided commands such that the resulting state is the correct outcome after executing the two commands in an adversarially-controlled order. Put differently, there are no race conditions that cause the services to reach any kind of “weird state”. We will explain this property by analyzing the simulator’s actions when CreateNode and DeleteNode requests are interleaved.
- **Property 3:** An adversary who compromises services can only leverage them to damage other (uncompromised) services by leveraging OpenStack’s token mechanism for authentication and authorization. Our ideal worlds accurately reflect the extent of the damage that the environment can cause by misusing acquired bearer tokens.

We will showcase this property by considering an adversary who has compromised only Nova (and not any other services) and who is trying to glean as much information as possible from Glance. In section 5 and 6, we will show the analogous property using a stronger ‘one-time’ token mechanism, in which the simulator responds slightly differently when dealing with service-to-service interactions.

4.4.1 Property 1: single command

By inspecting a sample command DeleteNode, we show that the view of the Environment E is the same for the ideal and OpenStack Services world. For the ideal world, the simulator S emulates the entire work flow that is required to process a single user-provided command, when viewed standalone.

In the OpenStack Services world, E interacts with the cloud services through \mathcal{F}_{ExtNet} and \mathcal{F}_{SMT} . To validate that the OpenStack Services doesn’t leak more information than the ideal cloud, S emulates the leakage of \mathcal{F}_{ExtNet} and \mathcal{F}_{SMT} in the OpenStack Services.

For the DeleteNode command, as illustrated in Figure 3, the following four type of messages are leaked through \mathcal{F}_{ExtNet} and \mathcal{F}_{SMT} (in the OpenStack Services) which the simulator S is in charge to emulate them:

Type-1: A “Delete Node” message from \mathcal{F}_{ExtNet} of the form $(U_{Dashboard}, \mathcal{F}_{Compute}, \text{“Delete Node”}, \text{session-id, node-id, user-id})$ sent in Step 3 in Figure 3.

Type-2: A “Delete Node Validation” message from \mathcal{F}_{SMT} of the form $(\mathcal{F}_{Compute}, \mathcal{F}_{Identity}, \text{“Service Validation”}, \text{session-id, Compute-id, user-id, “Delete node-id”})$ sent in Step 7 in Figure 3.

Type-3: A “Delete Node Validated” message from \mathcal{F}_{SMT} of the form $(\mathcal{F}_{Identity}, \mathcal{F}_{Compute}, \text{“Service Validated”}, \text{session-id, user-id, Compute-id, “Delete node-id”}, \text{valid})$ sent in Step 11 in Figure 3.

Type-4: A “Notification” message from \mathcal{F}_{ExtNet} of the form $(\mathcal{F}_{Compute}, U_{Dashboard}, \text{“Delete Node”}, \text{session-id, node-id, result})$ sent in Step 15 in Figure 3.

In OpenStack Services, when the `deletenode` command is executed, the first message that E gets is the Type-1 message, which indicates the command that is requested by the user.

In response, the simulator S acts as follows. Upon receiving a delete node “Request-message” from \mathcal{F}_{Cloud} , S runs the Dashboard protocol of the user with user-id with the input-message “Request-message.” This command activates \mathcal{F}_{ExtNet} with $(U_{Dashboard}, \mathcal{F}_{Compute}, \text{“Delete Node”}, \text{session-id, node-id, creds})$ and returns a Type-1 message to S . Then, S forwards this message to E .

When E hands back the control to the OpenStack Services by sending the message (“confirmation”, session-id), the Compute service then sends a validation request to Identity service which is leaked to E through \mathcal{F}_{SMT} (Type-2 message).

In order to emulate this leakage so that E ’s view is the same in both worlds, the simulator S sends the environment’s message back to the ideal cloud because it needs to know the validation result of the “Delete Node” request.

Upon receiving the reply from \mathcal{F}_{Cloud} of the form $(U_{Dashboard}, \text{“Delete Node”}, \text{session-id, user-id, node-id, valid})$, S stores the message in its buffer with `StoreBuffer(Receiver, “Delete Service Validation”, session-id, Compute-id, user-id, node-id, valid)`. Using the message given by \mathcal{F}_{Cloud} , S creates a Type-2 message and sends it to E . Note that the corresponding “Delete Node” message has already been buffered in \mathcal{F}_{Cloud} , which means that \mathcal{F}_{Cloud} and $\mathcal{F}_{Compute}$ are in the same consistent state.

When E hands back control to the OpenStack Services, the Identity service provides the validation result in the Type-3 format. This message is leaked through \mathcal{F}_{SMT} to E .

For S to create Type-3 message, it needs the validation result, which already exists in its buffer. Therefore, the simulator responds to E with a Type-3 message based on the validation result that has been stored in its buffer.

Upon getting the control back from E , the node is deleted (if it exists) by Compute service and the result message (Type-4) is leaked to E through \mathcal{F}_{ExtNet} .

However, in the ideal cloud, the node has not been deleted yet, this is why the simulator sends \mathcal{F}_{Cloud} a message of the form (“Delete Node”, session-id, Continue).

Upon receiving the reply from \mathcal{F}_{Cloud} of the form (“Delete Node”, session-id, NodeExist), S updates the buffer with the node existence information. Note that S does not send the node existence information, but uses it together with valid value to create Type-4 message. S sets “result” as “Success” if the buffered variables `Valid = 1 and NodeExist = 1`, and sets as “Fail” otherwise. Then S creates Type-4 message and sends it to E .

When E hands back the control to the OpenStack Services, the user then receives the result message, thus S sends a message to \mathcal{F}_{Cloud} which enables \mathcal{F}_{Cloud} to inform the user with the operation result.

For `DeleteNode` command, since the messages that leak from the ideal world/ S are the same as the messages that leak from the OpenStack Services, the environment cannot distinguish between these two worlds.

4.4.2 Property 2: multi command

In this section we explain how interleaving of two different user-provided commands maintains our invariant even when the adversary controls the order on intermediate message passing. More precisely, we analyze the simulator’s actions precisely to verify that E sees the same view in both worlds even when `CreateNode` and `DeleteNode` requests are interleaved.

In the OpenStack Services world, the DeleteNode command consists of the following steps:

1. User sends a “Delete Node” request with a unique session-id and a node-id to $\mathcal{F}_{Compute}$.
2. $\mathcal{F}_{Compute}$ validates that the user has permissions to delete a node by asking $\mathcal{F}_{Identity}$.
3. If the user is able to delete the node, $\mathcal{F}_{Compute}$ makes sure that the node with node ID=node-id exists and if so, deletes the node.
4. $\mathcal{F}_{Compute}$ notifies the user about the result.

The CreateNode command consists of several steps as follows:

1. User sends a “Create Node” request with a unique session-id and required specification, such as image-id to $\mathcal{F}_{Compute}$.
2. $\mathcal{F}_{Compute}$ validates the user to create a node with the specified *specification* by asking $\mathcal{F}_{Identity}$.
3. If the user is allowed to create the node –the validation result is true, then $\mathcal{F}_{Compute}$ requests the corresponding image of image-id from \mathcal{F}_{Image} .
4. \mathcal{F}_{Image} validates the user’s permissions to extract the image corresponding to image-id by asking $\mathcal{F}_{Identity}$. It sends the result to $\mathcal{F}_{Compute}$.
5. If the user is allowed to get the corresponding image of image-id, $\mathcal{F}_{Compute}$ requests a node-id from adversary.
6. Adversary provides a node-id.
7. $\mathcal{F}_{Compute}$ makes sure that the node-id is not used, if so, creates a node using the corresponding image and the specification and assigns the node-id to it.
8. $\mathcal{F}_{Compute}$ notifies the user about the result.

We emphasize the following properties of the two processes. First, the DeleteNode process shows that the node-id is evaluated only after $\mathcal{F}_{Compute}$ is sure that the user is allowed to delete the node and that the node exists. Second, the CreateNode process permits the node to be created only after step 6 in which the adversary provides the node-id.

Let’s consider the situation in which the user first runs the DeleteNode command for node-id =2 (which exists) then requests to “create a node” in which the adversary provides node-id =2 (in step 6 of the CreateNode command). We argue that, based on how the adversary may control the order of the intermediate messages, the result and E ’s view of these two commands in both worlds (OpenStack Services and ideal world) are the same and the simulator may never get to an undefined state. Note that the result may be different based on the adversarially-chosen order of intermediate messages, but the point here is that the two worlds provide the same result for each possible message ordering.

In the OpenStack Services, if the requests are done in the given order, the node with node-id =2 should be deleted first and a new node with node-id =2 be created next. However, if the adversary prevents the delete node to be deleted and lets the create node complete first, then the node wouldn’t be created because the node-id =2 is being used.

The simulator should also be able to act in the same way while not getting into an unexpected state. Note that validation of the user credentials and access list of one command doesn't affect the result of any other command. Therefore, we divide the CreateNode process into two phases.

Phase 1: Before getting node-id from the adversary (steps 1-5).

Phase 2: Getting node-id from the adversary and after that (steps 6-8). Note that in these steps, $\mathcal{F}_{Compute}$ executes without interruption from the adversary (or anyone else).

Phase 1 only deals with validation and getting corresponding image of image-id. During this phase, the ideal cloud provides the corresponding information by sending one of these two messages:

Type-A: (Receiver, “Get Node ID”, session-id, user-id, image-id, Corresponding-Image) for the case where the user is able to create a node and get the corresponding image related to image-id or

Type-B: (Receiver, “Create Node”, session-id, user-id, Fail, reason) for the case where the act of creating a node fails for reason = “user is not valid to create a node” or “user is not valid to get image related to image-id”.

If S has received a Type-B message from the cloud, the CreateNode command has failed due to invalid user permissions. In this case, any ordering of CreateNode and DeleteNode may not result into unexpected state for S because the validation messages have no effect on the result of any other message.

When the simulator receives a Type-A message, then the user is authorized to create a node and get the image related to image-id. Therefore, if all intermediate messages of *Phase 1* are sent, then the simulator can ask E for a node-id (which is the beginning of *Phase 2*).

If S receives a Type-A message, then the adversary can interleave messages in one of two ways:

1. The adversary might allow the DeleteNode command be completed before *Phase 2* of CreateNode command. In this case, the adversary has not given a node-id and thus the ideal cloud has not examined the usage of that node-id. Therefore, if the given node-id exists and the user is allowed to delete a node, the DeleteNode command will be done successfully and the create node can be completed with the same node-id.
2. The adversary might allow *Phase 2* of the CreateNode command to be completed before the DeleteNode command. In this case, the simulator has received the node-id for creating a node from the adversary. S then passes this message immediately to the cloud. At this state, the ideal cloud examines the node usage and if it is used (which in our case its true) then the result of create node will be “Fail” but the node is able to be deleted next.

In summary: while the adversary's choice of ordering messages can influence the final state, in both circumstances the outcome is identical in the OpenStack Services and ideal cloud, which means that E 's view must also be identical in both worlds. In particular, the simulator never reaches a state that is not defined by the services, and the execution of its commands yields the same result as the OpenStack Services when the adversary controls the message ordering.

4.4.3 Property 3: service compromise

In this section, our aim is to showcase how the simulator acts when having a compromised service such that the environment E sees the same view in both worlds.

Note that when a service is compromised, no matter which token mechanism is used, the adversary can do anything within the service's authority. Meanwhile, dealing with another service (when one of them is compromised) is not possible without using a token mechanism. Using the compromised service's capabilities, the adversary may try to deceive an uncompromised-service to get more information. In order to make this happen the adversary needs to send legitimate token with its request while dealing with *service-to-service* interaction. This is where the difference in security provided between the bearer token and the forthcoming, stronger one-time token model in Sections 5 and 6 can be demonstrated. For this reason, we will focus more on the service-to-service interactions and show how the simulator acts per each token models such that the environment E gets the same view in both worlds. We exemplify this scenario by discussing the case in which the adversary has compromised only Nova and is trying to get as much information as possible from Glance.

We illustrate Property 3 with Nova as the compromised service because several bearer tokens pass through Nova that are intended for different services. Ergo, a compromised Nova offers a representative case study for capturing the amount of damage that an active adversary can do; any other service-to-service interaction involves comparable or simpler reasoning.

In general, when Nova is compromised, the adversary gets access to credentials corresponding to the following:

- Any actions that users make of $\mathcal{F}_{Compute}$ while it is compromised.
- Any actions that users requested of $\mathcal{F}_{Compute}$ before it was compromised but that remained unfulfilled before the compromise.

Recall that in the ideal world there are no credentials; ergo, it is the simulator's responsibility to create, store, and track any compromised credentials as needed so that E sees the same result from both worlds for both models. Below, we consider the simulator's responsibility in each of the two token models.

Property 3 in the bearer token model The bearer token has two properties: 1- Unscoped, 2- No limitation on the number of usage. In the OpenStack Services, because of the first property, the adversary may make different requests to different services using the compromised service and user-id. And because of the second property, the adversary may use the compromised user-id and send a request to a service more than once.

The simulator should represent these properties in any condition, specially when a service is compromised, such that the environment E gets the same view from both worlds. To realize these properties, the simulator creates a credential per each compromised user (user-id). That is, when Nova is compromised, the simulator notifies the ideal cloud and the ideal cloud sends all user-id (together with their roles) that have made either a new request or have an unfinalized request while Nova was corrupted. Then, the simulator creates a unique credential for each user-id, stores it in its database for future use, and adds these credentials to the corresponding messages as needed. Having these credentials however, the simulator is not able to respond to the adversarial validation

request for a compromised user-id because in this case the simulator does not have the list of roles assigned to the manipulated user.

As an example, let's consider that Nova is compromised while user with user-id =5 has un-completed request and this user is able to have access to images related to image-id =2,10. In this situation, if the adversary/ E makes the following request to Glance (in the openstack world): "GetImage with image-id =2 for user-id =5", the Glance sends a request to Identity to validate user access and receives back the response. Based on the validation result, Glance provides the corresponding image to Compute. In the ideal world, the simulator is responsible to create these intermediate messages. Simulator has answer to neither Glance's validation request nor image, therefore it should ask the ideal cloud.

The simulator first makes sure that the user credential related to user-id =5 is correct by comparing it with the information in its database, then sends a request to the ideal cloud to get the validation result and the image related to the image-id =2. Based on the ideal cloud's response, the simulator creates the corresponding messages and sends it to E .

Because of "unlimited time of use" property that bearer token has, the adversary is able to repeat this request at any time. Which means all image information associated with image-id =2 for the rest of time should be considered compromised. In addition, due to the unscoped property, the simulator only stores a credential per user-id and therefore, the adversary is able to make another request to Glance to extract the image related to image-id =10 successfully (if s/he uses the same credential). Hence, E 's view will be identical in both worlds while using bearer token mechanism.

5 Improved Tokening Mechanism

Our analysis has shown that the simulator of the ideal cloud cannot emulate the corrupted services unless we relax the security promises of the ideal cloud. These concerns arise due to the use of bearer tokens, which enable anyone who can see a token to masquerade as corresponding user and perform any action allowed to the owner of the token on behalf of him. Bearer-tokens are leaked to the adversary in both partially and fully corrupted services which could happen through a vulnerability. Once a service corrupted, it could be malicious in at least two important ways:

- A service can use a token to obtain unrequested services charged to the user.
- A service can use a token to access other resources at another service (like exporting a disk with sensitive information).

The above problems are not tolerated by the cloud users. Having a bug free cloud is not realistic, but reducing effects of buggy code is possible. Therefore, it is desired to have OpenStack guarantee the modularity security requirement defined as follows.

Modularity Security Requirement If an adversary corrupts a service, other services just do whatever requested to do by the users, nothing more. For example, if an adversary corrupts the Image service, he cannot create or delete a node, but if a user issues a "create node" command, it is possible to create a node with a corrupted image because of the image service corruption.

We propose to limit the impact of service corruption by preventing replay attacks and scoping tokens only to handle the request desired by the user (following an idea laid out in [29, 24]). As a result, even if an attacker captures a credential submitted to a non-Keystone service by an honest user, he cannot do anything more on behalf of the user. In this section, we explain our two proposals for the OpenStack token issue which improve current security guarantees: 1) Ticketing System, and 2) Recursive Augmented Fernet Tokens. Then, in Section 6 we analyze OpenStack with our proposed scheme in order to demonstrate rigorously that our token mechanism realizes our goal of providing security in the face of service corruptions.

5.1 Ticketing System

A one-time use token scoped to a specific job resembles a “ticket” as used in Kerberos [42] or in TLS 1.3’s zero round trip time mechanism [43]. A ticket cannot be used more than one time and it is not possible to use it for any arbitrary action. Therefore, one option can be to replace the current bearer-token mechanism with a ticketing system as follows:

1. User asks Keystone for a ticket scoped to a specific job (e.g. delete a node, attach a volume, upload an image). Additionally, the user with the help of Dashboard protocol provides the restriction list required for the unique job such as node Id, volume Id, hash of the image, and the list of services that will be involved in the job processing steps.
2. Keystone creates a ticket for the request, stores the ticket and the list of the services required for the request in its DB, and sends the ticket to the user. Tickets are supposed to be used immediately by users. Therefore, they have a very short expiration time and the DB can be implemented in ephemeral memcached memory.
3. The User sends the ticket to the first service.
4. The first service asks Keystone to validate the ticket.
5. If the ticket and the name of the service exist in the DB, Keystone removes the name of service from the corresponding service list and returns True. Otherwise, it returns False. If the list of services is empty, the ticket is removed from the keystone’s memory.

The ticketing system is specified fully in Algorithm 27.

Pros and cons. The proposed ticketing system is a simple and straightforward mechanism for providing the modularity security requirement. It keeps the token (ticket) size small. However, the user needs to have an extra communication with Keystone to get a ticket for each request. Hence, a major change is needed for all the user interfaces.

5.2 RAFTs

The main drawback of the ticketing system is that a major change must be made to OpenStack to implement it. Here, we propose a new, backwards-compatible Fernet extension that we call Recursive Augmented Fernet Tokens (RAFTs), on top of which user-specified restrictions can float independently without requiring additional Keystone interaction. The RAFT token mechanism provides the modularity security requirement in the presence of one or more corrupted services just as ticketing accomplished. Fundamentally, RAFTs use the Fernet HMAC as a shared secret between the user and Keystone that can be used to authenticate arbitrary user-supplied restrictions.

Algorithm 27 Ticketing System

```
1: function IDEAL IDENTITY
2:   Upon receiving (creds, Job-Type, Restriction-List) from User U:
3:   if creds is valid then
4:     Create ticket for the Job using {Job-Type, Restriction-List, U};
5:     StoreDB(ticket, Service-List);
6:     return ticket;
7:   else
8:     return “fail”;
9:   end if
10:
11:   Upon receiving ( $\mathcal{F}_{Service}$ ,  $\mathcal{F}_{Identity}$ , “Validate”, ticket) from  $\mathcal{F}_{Service}$ :
12:   if FindBD(ticket, Service-List) where the ticket is valid and  $\mathcal{F}_{Service}$  is in the Service-List
13:   then
14:     New-Service-List=Remove  $\mathcal{F}_{Service}$  from the Service-List;
15:     if New-Service-List is Empty then
16:       RemoveDB(ticket, Service-List);
17:     else
18:       UpdateDB({ticket, Service-List }, {New-Service-List, ticket });
19:     end if
20:     Send- $\mathcal{F}_{Service}$  ( $\mathcal{F}_{Identity}$ , session-id, Successful);
21:   else
22:     Send- $\mathcal{F}_{Service}$  ( $\mathcal{F}_{Identity}$ , session-id, Fail);
23:   end if
24: end function
25: function SERVICE
26:   Upon receiving (Sender, ticket) from user U:
27:   StoreBuffer (Sender, ticket);
28:   Send- $\mathcal{F}_{Identity}$  ( $\mathcal{F}_{Service}$ , “Validate”, ticket);
29:
30:   Upon receiving ( $\mathcal{F}_{Identity}$ , session-id, valid) from  $\mathcal{F}_{Identity}$ :
31:   if valid=1 & FindBuffer(Sender, ticket) where session-ID in the Job-Request=session-id
32:   then
33:     Apply the Request;
34:   else
35:     Return Fail;
36:   end if
37: end function
```

The Fernet token is a recent innovation that uses cryptography to provide authenticity without accessing a central DB. It is a mechanism by which Keystone creates a private, authenticated channel to itself. It has quickly become the preferred token format for OpenStack as it does not require maintaining a central database of valid tokens, which would add network load and complexity when running a distributed Keystone service. The current Fernet token mechanism is [44]. The Fernet token is represented as follows:

$$Sk = \text{Keystone signing key}$$

$$Token_{Fernet} = Specification \parallel HMAC_{Sk}(Specification)$$

Because the original Fernet token is a bearer one, the link between the user and Keystone must be authenticated and encrypted to ensure that only the user receives $Token_{Fernet}$ from Keystone.

In RAFT, a user first obtains a Fernet token from Keystone. The user takes the $HMAC_{Sk}(Specification)$ as a shared secret key Uk between Keystone and himself. Then, for each of his subsequent requests, the user calculates:

$$Token_{RAFT} = Request \parallel$$

$$Specification \parallel$$

$$Restrictions \parallel$$

$$HMAC_{Uk}(Request \parallel Specification \parallel Restrictions)$$

The *Restrictions* could be a composition of anything like a shortened expiration time (“expiration-time = 5 secs”) or endpoint restrictions (“service=cinder”). The RAFT token is a self-explained token and the user request is part of the token and there is no need to accompany the request with the token. Hence, the user just sends the RAFT token to the desired service. For the sake of backward compatibility, which we will talk about later, all the services continue to accept job requests in the format of $(Request, Token)$ where either $Token = Token_{RAFT} - Request$ or $Token = Token_{Fernet}$.

When a service receives $Token_{RAFT}$, the service forwards it to Keystone asking for validation. If the answer of Keystone was “valid”, the service extracts the *Request* and *Restrictions* from the token and gets the work done accordingly.

In the current OpenStack architecture, each service gets a service token from Keystone. The service token is used to authenticate the service to other services [45]. RAFT replaces this bearer token as well: the token of a service is never sent to other services, but is instead used as a signing key Svk in the RAFT framework. Concretely, if a service needs to involve other services, then it calculates:

$$Svk = \text{Service signing key, from Keystone}$$

$$New_Token_{RAFT} = Token_{RAFT} \parallel$$

$$Restrictions \parallel$$

$$ServiceId \parallel$$

$$HMAC_{Svk}(Token_{RAFT} \parallel Restrictions),$$

and sends the result to the required services. We highlight three tangible benefits of this method: each service is able to add (but not remove!) *Restrictions* to the user’s token, the MAC authenticates

the channel used to make a service-to-service request, and the token provides the recipient service with the provenance of the request [45].

When Keystone receives a token validation request from a service S for token T , it follows the Fernet protocol as if T is a Fernet token. Keystone looks into its blacklist to see whether T was used by S or not. If yes, Keystone returns fail. Otherwise, Keystone validates all the service signatures. Then, it takes out *Specification* from T and calculates $HMAC_{S_k}(Specification)$ as its signing key. Using the result, Keystone is able to verify the user’s signature embedded into T , too. If the token is valid, Keystone adds (T, S) to its blacklist and returns “valid”. Just as in the ticketing system, the expiration time of RAFT tokens are very short. Therefore, the blacklist can be implemented in a lightweight memcached structure.

The RAFT is specified fully in Algorithm 28.

Pros and cons. RAFT uses the Fernet token to create a user to keystone private/authenticated channel, while not jeopardizing keystone’s existing channel to itself. It can be implemented in a backward compatible way. RAFT tokens are larger than Fernet tokens and the size of buffers used for storing tokens in different OpenStack modules must be carefully inspected.

5.3 Effect of One-Time Tokens on Corruption

Restricting tokens to be single use with specific parameters limits the scope of adversarial corruptions. Previously a corrupted service could store all tokens it sees and use them at will. This modification ensures that once a token has been used it will not be accepted again in the future. Additionally, since tokens are scoped, it is not possible for a corrupted service to lie to uncorrupted services about the content of a user’s request. Specifically, users will indicate when requesting a token exactly which of their resources it grants access to. This would not prevent a corrupted Compute from deleting a node when a user had asked to create one or creating a node with a completely different specification since Compute could simply do these things without bothering to verify the token, but it *would* prevent Compute from requesting a different image from the Image service than the one the user had intended. This helps in the case where the adversary has not already seen, via a request by a different user, the image it would like to have Compute use. Scoped, single use tokens even benefit functionalities that go beyond those captured in our model; for example, an adversary who corrupted the Compute service would be unable to upload arbitrary images.

We also remark that there is another notion of limited-use tokens with a security-performance tradeoff. Many OpenStack engineers desire a stateless Keystone architecture in order to distribute the authentication process over several servers and improve scalability and performance. If it is desirable to keep Keystone stateless, then one could instead design “limited-reuse” tokens with a short lifetime. While one could model the impacts of limited reuse by combining rate limiting with a UC model of network time [25], in this paper we focus on the One-Time token presented above with an explicit blacklist to prevent reuse.

Juxtaposing the ideal clouds in the bearer token (Algorithm 8) and One-Time token (Algorithm 29) scenarios is quite illustrative. An OpenStack developer who might not understand the full complexity of UC (and thus who might ignore our simulators and proofs) can still compare those two algorithms to understand the harms of partial compromise in the two settings. For example, Algorithm 8 shows that a corrupted $\mathcal{F}_{BlockStorage}$ can tamper with the delivery of an image from \mathcal{F}_{Image} to $\mathcal{F}_{Compute}$ during a Create Node operation in the bearer token model, whereas Algorithm 29 shows that the same attack is not possible in the ideal cloud for the One-Time token model.

Algorithm 28 Recursive Augmented Fernet Token

```
1: function IDEAL IDENTITY
2:   Upon receiving (creds, TokenRequest) from User U:
3:   if creds is valid then
4:     Create Token using the specification of U stored in the Keystone;
5:     return Token;
6:   else
7:     return “fail”;
8:   end if
9:
10:  Upon receiving ( $\mathcal{F}_{Service}$ ,  $\mathcal{F}_{Identity}$ , “Validate”, Token) from  $\mathcal{F}_{Service}$ :
11:  if Token is in Fernet format then
12:    Invoke Fernet-Validation-Protocol;
13:  else
14:    if Token is in RAFT format then
15:      try{
16:        assert(Token ExpirationTime –  $\mathcal{F}_{Service}$  Allowance < current-time);
17:        assert(All service signatures inside Token are valid);
18:        Specification = Extract-Specification(Token);
19:        Request = Extract-Request(Token);
20:        Uk =  $HMAC_{SK}$ (Specification) ;
21:        UserSign =  $HMAC_{UK}$ (Request || Specification);
22:        UserSign' = Extract-UserSign(Token);
23:        assert(UserSign = UserSign');
24:        assert(FindDB(Token,  $\mathcal{F}_{Service}$ ) = NULL);
25:        Send- $\mathcal{F}_{Service}$  ( $\mathcal{F}_{Identity}$ , session-id, Successful);
26:      }catch{
27:        Send- $\mathcal{F}_{Service}$  ( $\mathcal{F}_{Identity}$ , session-id, Fail);
28:      }
29:    end if
30:  end if
31: end function
32: function SERVICE
33:   Upon receiving (Sender, Token) from user U:
34:   Request = Extract-Request(Token);
35:   if Sender is allowed to do Request then
36:     StoreBuffer (Sender, Token, session-id);
37:     Send- $\mathcal{F}_{Identity}$  ( $\mathcal{F}_{Service}$ , “Validate”, Token);
38:   end if
39:
40:   Upon receiving ( $\mathcal{F}_{Identity}$ , session-id, valid) from  $\mathcal{F}_{Identity}$ :
41:   if valid = “Successful” & FindBuffer(Sender, Token, session-id) then
42:     Apply the Request;
43:   else
44:     Return Fail;
45:   end if
46: end function
```

```

47: function DASHBOARD
48:   Upon receiving (Sender, Token) from Keystone:
49:      $Uk = \text{Extract-Token-Sign}(Token)$  ;
50:      $Specification = \text{Extract-Specification}(Token)$ ;
51:
52:   Upon receiving ( $\mathcal{F}_{Service}$ , Request, Restrictions) from user U:
53:      $Specification' = Request \parallel Specification \parallel Restrictions$ ;
54:      $Token = Specification' \parallel HMAC_{UK}(Specification')$ ;
55:     Send- $\mathcal{F}_{Service}$  (U, Token);
56: end function

```

In the next section, we formalize this intuition and demonstrate that OpenStack with a one-time token model UC-realizes a stronger ideal cloud.

More generally, the UC ideal cloud that models any suggested security improvement permits OpenStack developers to understand concretely the value added by this improvement. This is an example for how UC modeling can provide developers with a valuable new tool that they can use to balance the relative importance of addressing any of the numerous bug reports on their plate at any given time.

6 UC Analysis of OpenStack with Improved Tokening Mechanism

In this section we aim to analyze the security of the strengthened version of OpenStack in the universal composability setting. Particularly, we want to prove the following theorem:

Theorem 3. *The strengthened version of OpenStack Services using RAFT securely realizes the less-leaky version of \mathcal{F}_{Cloud} in Algorithm 29 (in section 6.1) in the $(\mathcal{F}_{ExtNet}, \mathcal{F}_{SMT})$ -hybrid model.*

For this reason, we need to formally specify the ideal cloud and strengthened version of OpenStack Service in UC syntax, provide a simulator, and analyze that the simulator works to insure that the views of the environment is the same in both worlds. The rest of this section covers these purposes.

Note that all description and assumption made in section 3 holds for these algorithms.

6.1 Ideal Cloud Functionality Improved Tokens

We provide the ideal cloud functionality for the scenario with improved tokens in Algorithm 29 ⁵.

⁵The description of notation used in the algorithm is provided in appendix A

Algorithm 29 Ideal Cloud with corrupted services for Improved Token

```
1: function CLOUD
2:
3:   Upon receiving ("Corrupt", Service, value) from Sim:
4:   Corrupt[Service]=value; % the default value=None. None indicates no corruption; Passive
   is the partial corruption, and Active is the full corruption
5:   if Service= $\mathcal{F}_{Image}$  & value!=None then
6:     if there are user requests that have not finalized then
7:       Add (user-id) to the List;
8:     end if
9:     send-Sim(DB of (image-id, corresponding-Image),List of (user-id));
10:  else if Service= $\mathcal{F}_{Compute}$  & value!=None then
11:    if there are user requests that have not finalized then
12:      Add (user-id) to the List;
13:      Send-Sim(List of (user-id));
14:    end if
15:  else if Service= $\mathcal{F}_{Identity}$  & value!=None then
16:    Send-Sim(DB of (user-id, roles));
17:  else if Service= $\mathcal{F}_{BlockStorage}$  & value!=None then
18:    if there are user requests that have not finalized then
19:      Add (user-id) to the List;
20:    end if
21:    Send-Sim(List of (user-id));
22:  else if Service= $\mathcal{F}_{Node}$  node-id & value!=None then
23:    if there are user requests that have not finalized then
24:      Add (user-id) to the List;
25:    end if
26:    Send-Sim(List of (user-id));
27:  else if Service= $\mathcal{F}_{Volume}$  volume-id & value!=None then
28:    if there are user requests that have not finalized then
29:      Add (user-id) to the List;
30:    end if
31:    Send-Sim(List of (user-id));
32:  end if
33:  Upon receiving (Receiver, "Access Node", session-id, creds, node-id, RequestActivity) from
   user U:
34:  if session-id =(U,N) where N non-repetitive for user U then
35:    StoreBuffer (Receiver, "Access Node", session-id, creds, node-id, RequestActivity);
36:  end if
37:  Send-Sim (Receiver, "Node Access", session-id, user-id, node-id, RequestActivity);
38:
```

```

39:   Upon receiving("Result Access Node", session-id) from Sim:
40:   if FindBuffer(Receiver, "Access Node", session-id, creds, node-id, RequestActivity, valid)
then
41:       if valid=True then
42:           results  $\leftarrow$  EXECUTE(AccessRequest);
43:           UpdateBuffer({Receiver, "Access Node", session-id, creds, node-id, RequestActivity,
valid}, {Receiver, "Access Node", session-id, creds, node-id, result, valid});
44:           Send-Sim ("Access Node", session-id, user-id, node-id, result, valid);
45:       end if
46:   end if
47:
48:   Upon receiving("Output Access Node", session-id) from Sim:
49:   if FindBuffer(Receiver, "Access Node", session-id, creds, node-id, results, valid) then
50:       Valid=valid;
51:       RemoveBuffer("Access Node", session-id, creds, node-id, results, valid);
52:       Output("Access Node", session-id, results, Valid) to Receiver;
53:   end if
54:
55:   Upon receiving ("Access Node", session-id, node-id, RequestActivity) from Sim:
56:   if Corrupt[Node node-id ]=Active then
57:       results  $\leftarrow$  EXECUTE(AccessRequest);
58:   else
59:       results = None
60:   end if
61:   Send-Sim("Access Node", session-id, node-id, RequestActivity, results)
62:
63:   Upon receiving (Receiver, "Attach Volume", session-id, creds, volume-id, node-id) from user
U;
64:   if session-id =(U,N) where N non-repetitive for user U then
65:       StoreBuffer(Receiver, "Attach Volume", session-id, creds, volume-id, node-id);
66:   end if
67:   Send-Sim(Receiver, "Attach Volume", session-id, volume-id, node-id);
68:
69:   Upon receiving ("Result Attach Volume", session-id) from Sim:
70:   if FindBuffer(Receiver, "Attach Volume", session-id, creds, volume-id, node-id, valid) then
71:       if valid=True AND attached-volume for node node-id is None AND attached-node for
volume volume-id is None then
72:           Set attached-volume for node node-id to volume-id

```

```

73:         Set attached-node for volume volume-id to node-id
74:         UpdateBuffer({Receiver, "Attach Volume", session-id, creds, volume-id, node-id,
valid) }, {Receiver, "Attach Volume", session-id, creds, volume-id, node-id, success })
75:         Send-Sim("Attach Volume", session-id, volume-id, node-id, success)
76:     else
77:         UpdateBuffer({Receiver, "Attach Volume", session-id, creds, volume-id, node-id,
valid) }, {Receiver, "Attach Volume", session-id, creds, volume-id, node-id, failure })
78:         Send-Sim("Attach Volume", session-id, volume-id, node-id, failure)
79:     end if
80: end if
81:
82: Upon receiving ("Output Attach Volume", session-id) from Sim:
83: if FindBuffer(Receiver, "Attach Volume", session-id, creds, volume-id, node-id, success)
then
84:     RemoveBuffer(Receiver, "Attach Volume", session-id, creds, volume-id, node-id, success)
85:     Output("Attach Volume", session-id, success) to Receiver
86: else if FindBuffer(Receiver, "Attach Volume", session-id, creds, volume-id, node-id, failure)
then
87:     RemoveBuffer(Receiver, "Attach Volume", session-id, creds, volume-id, node-id, failure)
88:     Output("Attach Volume", session-id, failure) to Receiver
89: end if
90:
91: Upon Receiving (Confirm, "Attach Volume" session-id, valid)
92: if FindBuffer(Receiver, "Attach Volume", session-id, creds, volume-id, node-id) then
93:     if user user-id is allowed to attach volume-id to node-id for session session-id then
94:         valid=True
95:     else
96:         valid=False
97:     end if
98:     if Corrupt[Identity]=Active then
99:         valid = value sent by Sim
100:    end if
101:    UpdateBuffer({Receiver, "Attach Volume", session-id, creds, volume-id, node-id },
{Receiver, "Attach Volume", session-id, creds, volume-id, node-id, valid })
102:    Send-Sim(Receiver, "Attach Volume", session-id, volume-id, node-id, valid)
103: end if
104:
105: Upon receiving ("Attach Volume", session-id, volume-id, node-id) from Sim;
106: if Corrupt[Compute]=Active OR Corrupt[Node node-id ]=Active then
107:     Set attached-volume for node node-id to volume-id
108: end if

```

```

109:   if Corrupt[Storage]=Active OR Corrupt[Volume volume-id ]=Active then
110:       Set attached-node for volume volume-id to node-id
111:   end if
112:   Send-Sim ("Detach Volume", session-id, volume-id, node-id);
113:   Upon receiving (Receiver, "Detach Volume", session-id, creds, volume-id, node-id) from
    user U;
114:   if session-id =(U,N) where N non-repetitive for user U then
115:       StoreBuffer(Receiver, "Detach Volume", session-id, creds, volume-id, node-id);
116:   end if
117:   Send-Sim(Receiver, "Detach Volume", session-id, volume-id, node-id);
118:
119:   Upon receiving ("Result Detach Volume", session-id) from Sim:
120:   if FindBuffer(Receiver, "Detach Volume", session-id, creds, volume-id, node-id, valid) then
121:       if valid=True AND attached-volume for node node-id is volume-id AND attached-node
    for volume volume-id is node-id then
122:           Set attached-volume for node node-id to None
123:           Set attached-node for volume volume-id to None
124:           UpdateBuffer({Receiver, "Detach Volume", session-id, creds, volume-id, node-id,
    valid) }, {Receiver, "Detach Volume", session-id, creds, volume-id, node-id, success } )
125:           Send-Sim("Detach Volume", session-id, volume-id, node-id, success)
126:       else
127:           UpdateBuffer({Receiver, "Detach Volume", session-id, creds, volume-id, node-id,
    valid) }, {Receiver, "Detach Volume", session-id, creds, volume-id, node-id, failure } )
128:           Send-Sim("Detach Volume", session-id, volume-id, node-id, failure)
129:       end if
130:   end if
131:
132:   Upon receiving ("Output Detach Volume", session-id) from Sim:
133:   if FindBuffer(Receiver, "Detach Volume", session-id, creds, volume-id, node-id, success)
    then
134:       RemoveBuffer(Receiver, "Detach Volume", session-id, creds, volume-id, node-id, suc-
    cess)
135:       Output("Detach Volume", session-id, success) to Receiver
136:   else if FindBuffer(Receiver, "Detach Volume", session-id, creds, volume-id, node-id, fail-
    ure) then
137:       RemoveBuffer(Receiver, "Detach Volume", session-id, creds, volume-id, node-id, failure)
138:       Output("Detach Volume", session-id, failure) to Receiver
139:   end if
140:
141:   Upon Receiving (Confirm, "Detach Volume" session-id, valid);

```

```

142:   if FindBuffer(Receiver, "Detach Volume", session-id, creds, volume-id, node-id) then
143:     if user user-id is allowed to detach volume-id from node-id session session-id then
144:       valid=True
145:     else
146:       valid=False
147:     end if
148:     if Corrupt[Identity]=Active then
149:       valid = value sent by Sim
150:     end if
151:     UpdateBuffer({Receiver, "Detach Volume", session-id, creds, volume-id, node-id },
{Receiver, "Detach Volume", session-id, creds, volume-id, node-id, valid })
152:     Send-Sim(Receiver, "Detach Volume", session-id, volume-id, node-id, valid)
153:   end if
154:
155:   Upon receiving ("Detach Volume", session-id, volume-id, node-id) from Sim;
156:   if Corrupt[Compute]=Active OR Corrupt[Node node-id ]=Active then
157:     Set attached-volume for node node-id to None
158:   end if
159:   if Corrupt[Storage]=Active OR Corrupt[Volume volume-id ]=Active then
160:     Set attached-node for volume volume-id to None
161:   end if
162:   Send-Sim ("Detach Volume", session-id, volume-id, node-id);
163:
164:    $C_1$ – Upon receiving (Receiver, "Create Node", session-id, user-id, image-id, Node-
Structure, ServiceObject-List) from U:
165:   if Corrupt[Compute]!="Active" then
166:     if session-id =(U,N) where N non-repetitive for user U then
167:       StoreBuffer (Receiver, "Create Node", session-id, user-id, image-id, Node-
Structure);
168:     end if
169:   end if
170:   Send-Sim (Receiver, "Create Node", session-id, user-id, image-id, Node-Structure,
ServiceObject-List);
171:
172:    $C_3I_{12}$ – Upon receiving ("Create Node Output", session-id) from Sim:
173:   if FindBuffer(Receiver, "Create Node Continue", session-id, node-id, valid) then
174:     Output("Node Created", session-id, node-id, valid) to Receiver;
175:   end if
176:
177:    $D_1$ – Upon receiving (Receiver, "Delete Node", session-id, node-id, user-id) from user U:
178:   if Corrupt[Compute]!="Active" then
179:     if session-id =(U,N) where N non-repetitive for user U then

```

```

180:         StoreBuffer (Receiver, "Delete Node", session-id, user-id, node-id);
181:     end if
182: end if
183: Send-Sim(Receiver, "Delete Node", session-id, user-id, node-id);
184:
185:  $AC_2$ – Upon receiving ("MainComputeCorrupt", request) from Sim:
186: if Corrupt[Compute]="Active" then
187:     Apply the request;
188:     Send-Sim("MainComputeCorruptResult",result);
189: end if
190:
191:  $D_3O_2$ – Upon receiving (Receiver, "Delete Node", session-id, node-id, valid) from Sim:
192: if Corrupt[Compute]="Active" or Corrupt[Identity]="Active" then
193:     Output("Delete Node", session-id, node-id, valid) to Receiver;
194: end if
195:
196:  $D_3ID_4$ – Upon receiving ("Delete Node", session-id, node-id, valid) from Sim:
197: if FindBuffer(Receiver, "Delete Node", session-id, user-id, node-id) & Cor-
    rupt[Identity]="Active" then
198:     if valid=1 then
199:         if node node-id exists then
200:             NodeExist=1;
201:             Delete node with node-id;
202:         else
203:             NodeExist=0
204:         end if
205:         RemoveBuffer(Receiver, "Delete Node", session-id, user-id, node-id)
206:         Send-Sim (Receiver, "Delete Node Completed", session-id, user-id, node-id, valid,
    NodeExist);
207:     end if
208: end if
209:
210: Upon receiving ("Confirm", session-id) from Sim:
211: if FindBuffer(Receiver, "Create Node", session-id, user-id, image-id, Node-Structure) then
212:     if user-id is valid & user-id is allowed to create node using Node-Structure for this
    session-id then
213:         if Corrupt[Image]="Active" then
214:             UpdateBuffer({Receiver, "Create Node", session-id, user-id, image-id, Node-
    Structure},{Receiver, "Create Node", session-id, user-id, "Corrupted Get Image", Node-
    Structure})
215:              $C_3I_1$ – Send-Sim (Receiver, "Create Node", session-id, user-id, "Corrupted Get
    Image");
216:         else
217:             if user-id is allowed to create node with image-id with Node-Structure & there
    exists image-id then
218:                 Corresponding-Image=get the image corresponding to image-id;

```

```

219:         UpdateBuffer({Receiver, "Create Node", session-id, user-id, image-id,
Node-Structure},{Receiver, "Get Node ID", session-id, user-id, image-id, Node-Structure,
Corresponding-Image});
220:         C4I– Send-Sim(Receiver, "Get Node ID", session-id, user-id, image-id, Node-
Structure, Corresponding-Image); % GOTO C5I
221:         else
222:         UpdateBuffer({Receiver, "Create Node", session-id, user-id, image-id, Node-
Structure},{Receiver, "Create Node Continue", session-id, NULL, Fail});
223:         C4II– Send-Sim (Receiver, "Create Node", session-id, user-id, Fail, rea-
son="Get Image", Node-Structure);% GOTO C5II
224:         end if
225:         end if
226:         else
227:         UpdateBuffer({Receiver, "Create Node", session-id, user-id, image-id, Node-
Structure},{Receiver, "Create Node Continue", session-id, NULL, Fail});
228:         C4III– Send-Sim(Receiver, "Create Node", session-id, user-id, Fail, rea-
son="Create Node", Node-Structure);% GOTO C5III
229:         end if
230:         else if FindBuffer(Receiver, "Delete Node", session-id, user-id, node-id) then
231:         if user-id is valid & user-id is allowed to delete node node-id then
232:         Valid=1;
233:         else
234:         Valid=0;
235:         end if
236:         UpdateBuffer ({Receiver, "Delete Node", session-id, user-id, node-id },{Receiver,
"Delete Node", session-id, user-id, node-id, Valid});
237:         D4– Send-Sim (Receiver, "Delete Node", session-id, user-id, node-id, Valid);
238:         end if
239:
240:     C3C1O2– Upon receiving (Receiver, "Create Node result", session-id, node-id, valid) from
Sim:
241:     if Corrupt[Compute]="Active" then
242:         Output ("Node Created", session-id, node-id, valid) to Receiver;
243:     end if
244:
245:     C3I9– Upon receiving (Receiver, "Node ID", session-id, user-id, image-id, "Corrupted Get
Image",Corresponding-Image, node-id) from Sim:
246:     if Corrupt[Image]="Active" & FindBuffer(Receiver, "Create Node", session-id, user-id,
"Corrupted Get Image", Node-Structure) then
247:         if node-id is not used then
248:         UpdateBuffer({Receiver, "Create Node", session-id, user-id, "Corrupted Get Im-
age", Node-Structure}, {Receiver, "Create Node Continue", session-id, node-id, Successful});
249:         Add (node-id, user-id, Corresponding-Image, Node-Structure) to the list of active
nodes;
250:         Send-Sim("Create Node Continue", session-id, user-id, successful); % GOTO C3I10

```

```

251:     else
252:         UpdateBuffer({Receiver, "Get Node ID", session-id, user-id, image-id, Node-
Structure,, Corresponding-Image}, {Receiver, "Create Node Continue", session-id, node-id,
Fail});
253:         Send-Sim("Create Node Continue", session-id, user-id, Fail); % GOTO  $C_3I_{10}$ 
254:     end if
255: end if
256:
257:  $C_3C_1I_2$ – Upon receiving ("Get Image", session-id, user-id, image-id) from Sim:
258: if Corrupt[Compute]="Active" then
259:     if user-id is valid & user-id is allowed to apply Request session-id then
260:         valid=1;
261:         if image image-id exists then
262:             Corresponding-Image= extract corresponding image of image-id;
263:         else
264:             Corresponding-Image=NULL;
265:         end if
266:     else
267:         valid=0;
268:         Corresponding-Image=NULL;
269:     end if
270:     Send-Sim("Get Image", session-id, user-id, image-id, Corresponding-Image, valid); %
GOTO  $C_3C_1I_3$ 
271: end if
272:
273:  $C_3ID_8$ – Upon receiving ("Get Image", session-id, image-id) from Sim:
274: if Corrupt[Identity]="Active" then
275:     if image image-id exists then
276:         Corresponding-Image= extract corresponding image of image-id;
277:     else
278:         Corresponding-Image=NULL;
279:     end if
280:     Send-Sim("Get Image", session-id, image-id, Corresponding-Image);
281: end if
282:
283:  $C_3ID_{12}$ – Upon receiving ("Node ID", session-id, node-id, Corresponding-Image) from Sim:
284: if Corrupt[Identity]="Active" & FindBuffer(Receiver, "Create Node", session-id, user-id,
image-id, Node-Structure) then
285:     if node-id is not used then
286:         Add( node-id, user-id, Node-Structure, Corresponding-Image) to the list of active
nodes;
287:         UpdateBuffer({Receiver, "Create Node", session-id, user-id, image-id, Node-
Structure}, {Receiver, "Create Node Continue, session-id, node-id, Successful});
288:         Send-Sim("Create Node Continue", session-id, user-id, Successful);% GOTO  $C_3I_{10}$ 
289:     else

```

```

290:      UpdateBuffer({Receiver, "Create Node", session-id, user-id, image-id, Node-
Structure}, {Receiver, "Create Node Continue, session-id, node-id, Fail});
291:      Send-Sim("Create Node Continue", session-id, user-id, Fail);%GOTO C3I10
292:      end if
293:  end if
294:  C3ID5*– Upon receiving ("Create Node Output valid", session-id, valid) from Sim:
295:  if Corrupt[Identity]="Active" & FindBuffer(Receiver, "Create Node", session-id, user-id,
image-id, Node-Structure) then
296:    if valid=0 then
297:      Output("Create Node", session-id, NULL, Fail) to Receiver;
298:    end if
299:  end if
300:
301:  D8– Upon receiving ("Delete Node", session-id, Continue) from Sim:
302:  if FindBuffer(Receiver, "Delete Node", session-id, user-id, node-id, Valid) then
303:    if there is node with node-id then
304:      NodeExist=1;
305:    else
306:      NodeExist=0;
307:    end if
308:    UpdateBuffer({Receiver, "Delete Node", session-id, user-id, node-id, Valid}, {Receiver,
"Delete Node", session-id, user-id, node-id, Valid, NodeExist});
309:    if Valid=1 & NodeExist=1 then
310:      Delete node-id from the Node list;
311:    end if
312:    Send-Sim ("Delete Node Completed", session-id, Valid, NodeExist);
313:  end if
314:
315:  D11– Upon receiving ("Output Delete Node", session-id) from Sim:
316:  if FindBuffer(Receiver, "Delete Node", session-id, user-id, node-id, Valid, NodeExist) then
317:    if NodeExist=0 or Valid=0 then
318:      Output("Delete Node", session-id, node-id, Fail) to Receiver;
319:    else
320:      Output("Delete Node", session-id, node-id, Successful) to Receiver;
321:    end if
322:  end if
323:  C13I– Upon receiving ("Node ID", session-id, node-id) from Sim:
324:  if FindBuffer(Receiver, "Get Node ID", session-id, user-id, image-id, Node-Structure,
Corresponding-Image) then
325:    node-struct=Node-Structure;
326:    if node-id is not used then
327:      UpdateBuffer({Receiver, "Get Node ID", session-id, user-id, image-id, Node-
Structure, Corresponding-Image}, {Receiver, "Create Node Continue", session-id, node-id, Suc-
cessful});
328:      Add (node-id, user-id, Corresponding-Image, Node-Structure) to the list of active
nodes;

```

```

329:         Send-Sim("Create Node Continue", session-id, user-id, successful);
330:     else
331:         UpdateBuffer({Receiver, "Get Node ID", session-id, user-id, image-id, Node-
            Structure,, Corresponding-Image}, {Receiver, "Create Node Continue", session-id, node-id,
            Fail});
332:         Send-Sim("Create Node Continue", session-id, user-id, Fail);
333:     end if
334: end if
335:
336:  $C_9III, C_{13II}, C_{16I}$ – Upon receiving ("Create Node Output", session-id) from Sim:
337: if FindBuffer(Receiver, "Create Node Continue", session-id, node-id, valid) then
338:     Output("Create Node", session-id, node-id, valid) to Receiver;
339: end if
340: end function

```

6.2 OpenStack Services Functionalities Using One-Time Token

In the case of using One-time token, only Algorithm 10 and 25 are slightly changed. The new dashboard algorithm (Algorithm 30) creates one-time token credential per each request and adds it to the message before forwarding to the destination service.

The new identity algorithm (Algorithm 31) needs to make sure that the request is in the scope of the one-time token. It then adds the service (that made the validation request) to the session-id blacklist until the expiration of the one-time token.

Algorithm 30 Dashboard for one-time token

```

1: function DASHBOARD
2:
3:     Upon receiving Request-Message from Env:% The request-message also contains the expi-
        ration date and other information that are needed for the one-time Token
4:     Creates one-time token creds for the specific request with time and resource limitation based
        on the Request-Message, MasterToken and Key;
5:     Request-Message=Remove extra information that were needed to create one-time token
        from Request-Message;
6:     User U Creates ( $U_{Dashboard}, F_{Service}, Request-Message, creds$ );
7:     Send- $\mathcal{F}_{ExtNet}(Dashboard_U, F_{Service}, Request-Message, creds)$ ;
8:
9:     Upon receiving (Sender, Output-Message) from  $\mathcal{F}_{ExtNet}$ :
10:    Output (Output-Message) to Env;
11: end function

```

6.3 Simulator for Ideal Cloud with Improved Tokens

The simulator S for the ideal cloud using one-time token mechanism is given in Algorithm 32 ⁶. This simulator is more stringent than the simulator using bearer token model (Algorithm 26).

⁶The description of notation used in the algorithm is provided in appendix A

Algorithm 31 Identity for one-time token

```
1: function CORRUPT
2:   Upon receiving (“Corrupt”, Corrupt-Code) from Adv:
3:   Replace code of  $\mathcal{F}_{Identity}$  with code of Corrupted  $\mathcal{F}_{Identity}$ 
4: end function
5: function SERVICEVALIDATION %  $F_{Identity}$  removes the black list of the expired tokens;
6:   Upon receiving (Receiver, “Service Validation”, session-id,  $creds_{service}$ ,  $creds$ , Request) from
    $\mathcal{F}_{SMT}$ :
7:   if  $creds_{service}$  &  $creds$  are valid &  $creds$  is allowed to perform the Request then % here the
   validation means: 1)It computes the HMAC related to that user and then compares 2) The
   token is not expired 3) this service needs to take action but is not in  $BlackList_{session-id}$ .
8:     Add the service to  $BlackList_{session-id}$ ;
9:     valid=1;
10:  else
11:    valid=0;
12:  end if
13:  Send- $\mathcal{F}_{SMT}$  ( $\mathcal{F}_{Identity}$ , Receiver, “Service Validated”, session-id, user-id, service-id, Request,
   valid);
14: end function
```

To enforce the single-use constraint, S creates a black list to store the services that have already checked the validity of a credential using session-id; the simulator then rejects all future attempts to validate the same credential. To enforce the scoping constraint, S only issues credentials when given both an session-id *and* a request scope; the simulator records this intended scope and subsequently rejects all attempts to validate the credential in pursuit of a request outside of this scope.

6.4 Analysis

In this section, we explain how the OpenStack Services collectively UC-realize our Ideal Cloud in the one-time token scenario. Note that properties 1 and 2 of Section 4.4 continue to hold in the one-time token case because those properties only demonstrate correctness when all services are uncompromised, in which case there are no tokens (of any type) for the adversary to abuse. To complete the proof, we require two new properties.

- **Property 3’:** The view of E is identical in the less-leaky \mathcal{F}_{Cloud} and the OpenStack services even when services are compromised, as long as each observed token can only be used one time.
- **Property 4:** The cryptographic design of our stronger tokens ensures that each token may only be used once.

6.4.1 Property 3’: Service compromise using one-time token model

The one-time token has two properties: 1- Scoped and 2- One-time usage. In the OpenStack Services, because of the first property, the adversary is only able to make requests in the defined scope and because of the second property, the adversary is not able to reuse it to make a request to

Algorithm 32 Simulator with corrupted services for One-time token

```
1: function SIMULATOR(message)
2:
3:   Upon receiving ("Corrupt", Service,value) from Env:
4:   Corrupt[Service]=value;%value=passive or Active. For passive corruption, there would be
   no changes in the ideal cloud functionality. In this case, the credentials are leaked (which has
   not been written in the code.)
5:   Fetch Buffer and find all session-id which are not finalized when corruption happens and
   create unique Credential per each, then update BufferRequest with the new credential and set
   corruption value to "corrupt";
6:   if FindServiceCorrupt(Service, Service-id,  $creds_{service}$ ) &  $creds_{service} = \text{NULL}$  then
7:     Credential= Generate credential for the service;
8:      $creds_{service} = \text{Credential}$ ;
9:     UpdateServiceCorrupt(Service, Service-id,  $creds_{service}$ );
10:  end if
11:  Send-IdealCloud("Corrupt", Service, value);
12:  Upon receiving (DB of (image-id, corresponding-Image) from Ideal Cloud:
13:  StoreDB (All (image-id, corresponding-Image));
14:
15:  Upon receiving (List of active nodes) from Ideal Cloud:
16:  StoreDB (active nodes);
17:  Upon receiving (Sender, Receiver, message) from Env:
18:  if Receiver= $\mathcal{F}_{Compute}$  & Corrupt[Compute]="Active" then
19:    Send-Env(Sender, Adversary, message);
20:  else if Receiver= $\mathcal{F}_{Identity}$  & Corrupt[Identity]="Active" then
21:    Send-Env(Sender, Adversary, message);
22:  else if Receiver= $\mathcal{F}_{Image}$  & Corrupt[Image]="Active" then
23:    Send-Env(Sender, Adversary, message);
24:  else if Receiver= $\mathcal{F}_{BlockStorage}$  & Corrupt[Storage]="Active" then
25:    Send-Env(Sender, Adversary, message);
26:  else if Receiver= $\mathcal{F}_{Node}$ node-id & Corrupt[Node node-id ]="Active" then
27:    Send-Env(Sender, Adversary, message);
28:  else if Receiver= $\mathcal{F}_{Volume}$  volume-id & Corrupt[Volume volume-id ]="Active" then
29:    Send-Env(Sender, Adversary, message);
30:  end if
```

```

31:
32:   Upon receiving (Receiver, "Attach Volume", session-id, user-id, node-id) from Cloud:
33:   StoreBuffer(Receiver, "Attach Volume", session-id, user-id, node-id)
34:   Send-Env ( $\mathcal{F}_{Compute}$ , "Attach Volume", session-id, user-id, node-id)
35:
36:   Upon Receiving("Attach Volume", session-id, volume-id, node-id, success)
37:   StoreBuffer("Attach Volume", session-id, volume-id, node-id, success)
38:   Send-Env ( $\mathcal{F}_{Compute}$ , "Attach Volume", session-id, volume-id, node-id, success)
39:
40:   Upon Receiving("Attach Volume", session-id, volume-id, node-id, failure)
41:   StoreBuffer("Attach Volume", session-id, volume-id, node-id, failure)
42:   Send-Env ( $\mathcal{F}_{Compute}$ , "Attach Volume", session-id, volume-id, node-id, failure)
43:
44:   Upon Receiving("Attach Volume", session-id, volume-id, node-id, valid)
45:   StoreBuffer("Attach Volume", session-id, volume-id, node-id, valid)
46:   Send-Env ( $\mathcal{F}_{Identity}$ , "Attach Volume", session-id, volume-id, node-id, valid)
47:
48:   Upon receiving (Adversary,  $\mathcal{F}_{Compute}$ , "Attach Volume", session-id, node-id, RequestActiv-
ity) from Env:
49:   Send-IdealCloud(Adversary, "Attach Volume", session-id, node-id, RequestActivity)
50:
51:   Upon Receiving ("Attach Volume", session-id, volume-id, node-id)
52:   if (Compute is Corrupt OR Node node-id is Corrupt) AND (Storage is Corrupt OR Volume
volume-id is Corrupt) then
53:     Send-Env("Attach Volume", session-id, volume-id, node-id, success)
54:   else
55:     Send-Env("Attach Volume", session-id, volume-id, node-id, failure)
56:   end if

```

```

57:
58:   Upon receiving (Receiver, "Detach Volume", session-id, user-id, node-id) from Cloud:
59:   StoreBuffer(Receiver, "Detach Volume", session-id, user-id, node-id)
60:   Send-Env ( $\mathcal{F}_{Compute}$ , "Detach Volume", session-id, user-id, node-id)
61:
62:   Upon Receiving("Detach Volume", session-id, volume-id, node-id, success)
63:   StoreBuffer("Detach Volume", session-id, volume-id, node-id, success)
64:   Send-Env ( $\mathcal{F}_{Compute}$ , "Detach Volume", session-id, volume-id, node-id, success)
65:
66:   Upon Receiving("Detach Volume", session-id, volume-id, node-id, failure)
67:   StoreBuffer("Detach Volume", session-id, volume-id, node-id, failure)
68:   Send-Env ( $\mathcal{F}_{Compute}$ , "Detach Volume", session-id, volume-id, node-id, failure)
69:
70:   Upon Receiving("Detach Volume", session-id, volume-id, node-id, valid)
71:   StoreBuffer("Detach Volume", session-id, volume-id, node-id, valid)
72:   Send-Env ( $\mathcal{F}_{Identity}$ , "Detach Volume", session-id, volume-id, node-id, valid)
73:
74:   Upon receiving (Adversary,  $\mathcal{F}_{Compute}$ , "Detach Volume", session-id, node-id, RequestActiv-
ity) from Env:
75:   Send-IdealCloud(Adversary, "Detach Volume", session-id, node-id, RequestActivity)
76:
77:   Upon Receiving ("Detach Volume", session-id, volume-id, node-id)
78:   if (Compute is Corrupt OR Node node-id is Corrupt) OR (Storage is Corrupt OR Volume
volume-id is Corrupt) then
79:     Send-Env("Detach Volume", session-id, volume-id, node-id, success)
80:   else
81:     Send-Env("Detach Volume", session-id, volume-id, node-id, failure)
82:   end if
83:
84:    $C_2$ – Upon receiving (Receiver, "Create Node", session-id, user-id, image-id, Node-
Structure, ServiceObject-List) from Ideal cloud:
85:   StoreDBRequest(session-id, Request-Message, NULL, ServiceObject-List, NULL, NULL);
86:   StoreBuffer(Receiver, "Create Node", session-id, user-id, image-id, Node-Structure);
87:   Send-Env(Receiver,  $\mathcal{F}_{Compute}$ , "Create Node", session-id, user-id, image-id, Node-Structure,
ServiceObject-List);
88:

```

```

89:    $AC_1$ – Upon receiving (Adversary,  $\mathcal{F}_{Compute}$ , request) from Env:
90:   if Corrupt[Compute]="Active" then
91:     Send-IdealCloud("MainComputeCorrupt", request);
92:   end if
93:
94:    $C_3C_1I_3$ – Upon receiving ("Get Image", session-id, Corresponding-Image, valid) from IdealCloud:
95:     if FindBuffer("Result", Service, destination, message) with request-ID=session-id then
96:       UpdateBuffer({"Result",  $F_{Service}$ , destination, message}, { $\mathcal{F}_{Image}$ ,  $\mathcal{F}_{Compute}$ , "Get Image", session-id, image-id, Corresponding-Image, valid});
97:       StoreDB(image-id, Corresponding-Image);% if this image is not stored in the Sim DB, then store it.
98:       Send-Env( $\mathcal{F}_{Image}$ ,  $\mathcal{F}_{Identity}$ , "Service Validation", session-id, FImage-id, user-id, "Get Image image-id ");
99:     end if
100:
101:    $C_3I_2$ – Upon receiving (Receiver, "Create Node", session-id, user-id, "Corrupted Get Image") from Ideal Cloud:
102:     StoreBuffer(Receiver, "Service Validation", session-id, user-id, image-id, "Corrupted Get Image");
103:     Send-Env( $\mathcal{F}_{Compute}$ ,  $\mathcal{F}_{Identity}$ , "Service Validation", session-id, Compute-id, user-id, "Create Node");
104:
105:    $C_3ID_9$ – Upon receiving ("Get Image", session-id, image-id, Corresponding-Image) from Ideal Cloud:
106:     if Corrupt[Identity]="Active" & FindBuffer(Receiver,"Create Node Get Image result", session-id, user-id, image-id, Node-Structure, Image-valid) then
107:       if Corresponding-Image=NULL then
108:         valid=0;
109:       else
110:         valid=1;
111:       end if
112:       UpdateBuffer({Receiver,"Create Node Get Image result", session-id, user-id, image-id, Node-Structure, Image-valid},{Receiver,"Create Node Get Image continue", session-id, user-id, image-id, Node-Structure, Corresponding-Image, valid});
113:       Send-Env( $\mathcal{F}_{Image}$ ,  $\mathcal{F}_{Compute}$ , "Image", session-id, image-id, , Corresponding-Image);
114:     end if

```

```

115:
116:    $C_3I_{10}$ – Upon receiving ("Create Node Continue", session-id, user-id, valid) from Ideal-
      Cloud:
117:   if FindBuffer(Receiver, "Node ID continue", session-id, node-id) then
118:     UpdateBuffer({Receiver, "Node ID continue", session-id },{Receiver, "Create Node
      Output", session-id })
119:     Send-Env( $\mathcal{F}_{Compute}$ , Receiver, "Node Created", session-id, node-id, valid);%GOTO
       $C_3I_{11}$ 
120:   else if Corrupt[Identity]="Active" & FindBuffer(Receiver,"Create Node node ID", session-
      id, user-id, image-id, Node-Structure, Corresponding-Image, valid,node-id) then
121:     UpdateBuffer ({Receiver,"Create Node node ID", session-id, user-id, image-id, Node-
      Structure, Corresponding-Image, valid,node-id },{Receiver, "Create Node Output", session-id
      });
122:     Send-Env( $\mathcal{F}_{Compute}$ , Receiver, "Node Created", session-id, node-id, valid);%GOTO
       $C_3I_{11}$ 
123:   end if
124:
125:    $C_{12I}, C_3I_8, C_3ID_{11}$ – Upon receiving (Adversary,  $\mathcal{F}_{Compute}$ , "Node ID", session-id, node-id)
      from Env:
126:   if Corrupt[Image]="Active" & FindBuffer (Receiver, "Node ID", session-id, user-id, image-
      id, "Corrupted Get Image", Corresponding-Image) then
127:     UpdateBuffer({Receiver, "Node ID", session-id, user-id, image-id, "Corrupted Get Im-
      age", Corresponding-Image},{Receiver, "Node ID continue", session-id, node-id });
128:      $C_3I_8$ – Send-IdealCloud (Receiver, "Node ID", session-id, user-id, image-id, "Corrupted
      Get Image", Corresponding-Image, node-id);
129:   else if Corrupt[Identity]="Active" & FindBuffer(Receiver,"Create Node get node ID",
      session-id, user-id, image-id, Node-Structure, Corresponding-Image, valid) then
130:     UpdateBuffer({Receiver,"Create Node get node ID", session-id, user-id, image-id, Node-
      Structure, Corresponding-Image, valid},{Receiver,"Create Node node ID", session-id, user-id,
      image-id, Node-Structure, Corresponding-Image, valid,node-id })
131:      $C_3ID_{11}$ – Send-IdealCloud("Node ID", session-id, node-id, Corresponding-Image);
132:   else if FindBuffer(Receiver, "Request NodeID", session-id) then
133:     UpdateBuffer ({Receiver, "Request NodeID", session-id },{Receiver, "Node ID con-
      tinue", session-id, node-id })
134:     Send-IdealCloud ("Node ID", session-id, node-id);
135:   end if
136:
137:   Upon receiving (Adversary, Receiver, "Forward", message, destination) from Env:
138:   if Receiver= $\mathcal{F}_{Compute}$  & Corrupt[Compute]="Active" then
139:     if Destination is not a service then
140:       StoreBuffer("Output",  $\mathcal{F}_{Compute}$ , destination, message);
141:     else
142:       StoreBuffer( $\mathcal{F}_{Compute}$ , destination, message);
143:     end if

```

```

144:       $C_3C_1$ – Send-Env( $\mathcal{F}_{Compute}$ , destination, message);% FOR OUTPUT GOTO  $C_3C_1O_1$ ,
      ELSE GOTO  $C_3C_1ID_1$  [identity] OR  $C_3C_1I_1$  [glance]
145:      else if Receiver= $\mathcal{F}_{Identity}$  & Corrupt[Identity]="Active" then
146:          if destination= $\mathcal{F}_{Compute}$  & Request="Delete Node" & message is "Service Validated"
          type & FindBuffer(Receiver,"Corrupt Validated Delete Node", session-id, user-id, node-id)
          then
147:              extract the valid value from the message;
148:              UpdateBuffer({Receiver,"Corrupt Validated Delete Node", session-id, user-id, node-
              id }, {Receiver,"Corrupt Result Delete Node", session-id, user-id, node-id, valid});
149:               $D_3ID_2$ – Send-Env( $\mathcal{F}_{Identity}$ , destination, message);
150:              else if destination= $\mathcal{F}_{Compute}$  & Request="Create Node with Node-Structure" & mes-
              sage is "Service Validated" type & FindBuffer(Receiver,"Create Node validated", session-id,
              user-id, image-id, Node-Structure) then
151:                  extract the valid value from the message;
152:                  UpdateBuffer({Receiver,"Create Node validated", session-id, user-id, image-id,
                  Node-Structure}, {Receiver,"Create Node result", session-id, user-id, image-id, Node-Structure,
                  valid});
153:                   $C_3ID_2$ – Send-Env( $\mathcal{F}_{Identity}$ , destination, message);
154:                  else if destination= $\mathcal{F}_{Image}$  & Request="Get Image image-id " & message is "Service
                  Validated" type & FindBuffer(Receiver,"Create Node Get Image validated", session-id, user-id,
                  image-id, Node-Structure, valid) then
155:                      extract the Image-valid value from the message;
156:                      UpdateBuffer({Receiver,"Create Node Get Image validated", session-id, user-id,
                      image-id, Node-Structure, valid}, {Receiver,"Create Node Get Image result", session-id, user-
                      id, image-id, Node-Structure, Image-valid});
157:                       $C_3ID_6$ – Send-Env( $\mathcal{F}_{Identity}$ , destination, message);
158:                      else
159:                          StoreBuffer( $\mathcal{F}_{Identity}$ , destination, message);
160:                          Send-Env( $\mathcal{F}_{Identity}$ , destination, message);
161:                      end if
162:                  else if Receiver= $\mathcal{F}_{Image}$  & Corrupt[Image]="Active" then
163:                      if destination=  $\mathcal{F}_{Compute}$  & message=("Image", session-id, image-id, Corresponding-
                      Image ) & FindBuffer(Receiver, "Get Image Result", session-id, user-id, image-id, "Corrupted
                      Get Image") where the message session-ID=session-id then
164:                          UpdateBuffer ({Receiver, "Get Image Result", session-id, user-id, image-id, "Cor-
                          rupted Get Image"}, {Receiver, "Get Node ID", session-id, user-id, image-id, "Corrupted Get
                          Image", Corresponding-Image});
165:                      else
166:                          StoreBuffer( $\mathcal{F}_{Image}$ , destination, message);
167:                      end if
168:                   $C_3I_6$ – Send-Env( $\mathcal{F}_{Image}$ , destination, message);% GOTO  $C_3I_7ID_1$  [identity] OR  $C_3I_7$ 
                  [Compute])
169:                  end if

```

```

170:
171:   $C_3I_6^*$ – Upon receiving (Adversary,  $\mathcal{F}_{Image}$ , "Get Image", image-id) from Env:
172:  if Corrupt[Image]="Active" then
173:    if image-id exist then
174:      Corresponding-Image= extract the corresponding image for image-id;
175:    else
176:      Corresponding-Image= NULL;
177:    end if
178:    Send-Env ( $\mathcal{F}_{Image}$ , Adversary, "Image", image-id, Corresponding-Image );
179:  end if
180:
181:   $D_2$ – Upon receiving (Receiver, "Delete Node", session-id, user-id, node-id) from Ideal
    cloud:
182:  StoreDBRequest(session-id, Request-Message, NULL, ServiceObject-List, NULL, NULL);
183:  StoreBuffer(Receiver,"Delete Node", session-id, user-id, node-id);
184:  Send-Env(Receiver,  $\mathcal{F}_{Compute}$ , "Delete Node", session-id, node-id, user-id);
185:
186:   $AC_3$ – Upon receiving ("MainComputeCorruptResult", result) from IdealCloud:
187:  Send-Env ( $\mathcal{F}_{Compute}$ , Adversary, result); % GOTO  $C_3C_1$  (for forwarding), GOTO  $AC_1$  (for
    Adv to make new request)
188:
189:   $D_3ID_5$ – Upon receiving (Receiver, "Delete Node Completed", session-id, user-id, node-id,
    valid, NodeExist) from Ideal Cloud:
190:  StoreBuffer(Receiver, "Delete Node Completed", session-id, user-id, node-id, valid, Node-
    Exist);
191:  if valid=1 & NodeExist=1 then
192:    Send-Env( $\mathcal{F}_{Compute}$ , Receiver, "Delete Node", session-id, node-id, successful );
193:  else
194:    Send-Env( $\mathcal{F}_{Compute}$ , Receiver, "Delete Node", session-id, node-id, Fail );
195:  end if
196:
197:  Upon receiving ("Confirm", session-id) from Env:
198:  if FindBuffer(Receiver,"Create Node", session-id, user-id, image-id, Node-Structure) then
199:    if Corrupt[Compute]="Active" then
200:      if FindDBRequest(session-id, Request-Message, Credential, ServiceObject-List,
    Black-List, Corruption) & Corruption ="Corrupt" then
201:        creds =Credential, ServiceObject-List;
202:      else
203:        Credential= Generate credential for the user;
204:        creds = Credential, ServiceObject-List;
205:        UpdateDBRequest for session-id with the new credential value and set Corrup-
    tion="Corrupt";
206:      end if

```

```

207:       $C_3C$ – Send-Env(Receiver, Adversary, "Create Node", session-id, creds, image-id,
Node-Structure);% GOTO  $AC_1$  (Adv makes a new request),  $C_3C_1$  (for forwarding)
208:      else if Corrupt[Identity]="Active" then
209:        UpdateBuffer({Receiver,"Create Node", session-id, user-id, image-id, Node-
Structure},{Receiver,"Create Node validation", session-id, user-id, image-id, Node-Structure});
210:        Request="Create Node with Node-Structure";
211:         $C_3ID$ – Send-Env( $\mathcal{F}_{Compute}$ ,  $\mathcal{F}_{Identity}$ , "Service Validation", session-id, Service-id,
user-id, Request, ServiceObject-List);
212:        else if Corrupt[Image]="Active" then
213:           $C_3I$ – Send-IdealCloud("Confirm", session-id);
214:        else
215:           $C_3$ – Send-IdealCloud("Confirm", session-id);
216:        end if
217:      else if FindBuffer(Receiver,"Create Node validation", session-id, user-id, image-id, Node-
Structure) then
218:        if Corrupt[Identity]="Active" then
219:          if FindDBRequest(session-id, Request-Message, Credential, ServiceObject-List,
Black-List, Corruption) & Corruption ="Corrupt" then
220:            creds =Credential, ServiceObject-List;
221:          else
222:            Credential= Generate credential for the user;
223:            creds = Credential, ServiceObject-List;
224:            UpdateDBRequest for session-id with the new credential value and set Corrup-
tion="Corrupt";
225:          end if
226:          Extract credsservice from ServiceCorrupt(Service, Service-id, credsservice) where
Service= $\mathcal{F}_{Compute}$ ;
227:          UpdateBuffer({Receiver,"Create Node validation", session-id, user-id, image-id,
Node-Structure},{Receiver,"Create Node validated", session-id, user-id, image-id, Node-
Structure});
228:           $C_3ID_1$ – Send-Env ( $\mathcal{F}_{Compute}$ , Adversary, "Service validation, session-id, credsservice,
creds, Request); % GOTO  $D_3ID_2$  OR ADV MAY SEND ARBITRARY MESSAGE TO A
SERVICE
229:        end if
230:      else if FindBuffer(Receiver,"Create Node result", session-id, user-id, image-id, Node-
Structure, valid) then
231:        if Corrupt[Identity]="Active" then
232:          if valid=0 then
233:            UpdateBuffer({Receiver,"Create Node result", session-id, user-id, image-id,
Node-Structure, valid},{Receiver,"Create Node result continue", session-id, user-id, image-id,
Node-Structure, valid});
234:             $C_3ID_3^*$ – Send-Env( $\mathcal{F}_{Compute}$ , Receiver, "Create Node", session-id, NULL,
Fail);%GOTO  $C_3ID_4^*$ 
235:          else
236:            UpdateBuffer({Receiver,"Create Node result", session-id, user-id, image-id,
Node-Structure, valid},{Receiver,"Create Node Get Image", session-id, user-id, image-id, Node-
Structure, valid});

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237:       $C_3ID_3$ – Send-Env( $\mathcal{F}_{Compute}$ ,  $\mathcal{F}_{Image}$ , "Get Image", session-id, user-id, image-
id);%GOTO  $C_3ID_4$ 
238:      end if
239:      end if
240:      else if FindBuffer(Receiver,"Create Node result continue", session-id, user-id, image-id,
Node-Structure, valid) then
241:           $C_3ID_4^*$ – Send-IdealCloud("Create Node Output valid", session-id, Fail);
242:      else if FindBuffer(Receiver,"Create Node Get Image", session-id, user-id, image-id, Node-
Structure, valid) then
243:          UpdateBuffer({Receiver,"Create Node Get Image", session-id, user-id, image-id, Node-
Structure, valid},{Receiver,"Create Node Get Image validation", session-id, user-id, image-id,
Node-Structure, valid});
244:           $C_3ID_4$ – Send-Env( $\mathcal{F}_{Image}$ ,  $\mathcal{F}_{Identity}$ , "Service Validation", session-id, compute-id, user-
id, Request="Get Image image-id ");
245:      else if FindBuffer(Receiver,"Create Node Get Image validation", session-id, user-id, image-
id, Node-Structure, valid) then
246:          if Corrupt[Identity]="Active" then
247:              if FindDBRequest(session-id, Request-Message, Credential, ServiceObject-List,
Black-List, Corruption) & Corruption ="Corrupt" then
248:                  creds =Credential, ServiceObject-List;
249:              else
250:                  Credential= Generate credential for the user;
251:                  creds = Credential, ServiceObject-List;
252:                  UpdateDBRequest for session-id with the new credential value and set Corrup-
tion="Corrupt";
253:              end if
254:              Extract  $creds_{service}$  from ServiceCorrupt(Service, Service-id,  $creds_{service}$ ) where
Service= $\mathcal{F}_{Image}$ ;
255:              UpdateBuffer({Receiver,"Create Node Get Image validation", session-id, user-id,
image-id, Node-Structure, valid},{Receiver,"Create Node Get Image validated", session-id,
user-id, image-id, Node-Structure, valid});
256:           $C_3ID_5$ – Send-Env ( $\mathcal{F}_{Image}$ , Adversary, "Service validation, session-id,  $creds_{service}$ ,
creds, Request="Get Image image-id ");
257:      end if
258:      else if FindBuffer(Receiver,"Create Node Get Image result", session-id, user-id, image-id,
Node-Structure, Image-valid) then
259:          if Corrupt[Identity]="Active" then
260:              if Image-valid=0 then
261:                  UpdateBuffer({Receiver,"Create Node Get Image result", session-id, user-id,
image-id, Node-Structure, Image-valid}, {Receiver,"Create Node result continue", session-id,
user-id, image-id, Node-Structure, Fail});
262:           $C_3ID_7$ – Send-Env( $\mathcal{F}_{Compute}$ , Receiver, "Create Node", session-id, NULL,
Fail);%GOTO  $C_3ID_4^*$ 
263:      else
264:          UpdateBuffer({Receiver,"Create Node Get Image result", session-id, user-id,
image-id, Node-Structure, Image-valid},{Receiver,"Create Node Get Image result", session-id,
user-id, image-id, Node-Structure, Image-valid});

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265:          $C_3ID_7$ – Send-IdealCloud("Get Image", session-id, image-id);%GOTO  $C_3ID_8$ 
266:     end if
267: end if
268:     else if FindBuffer(Receiver,"Create Node Get Image continue", session-id, user-id, image-
id, Node-Structure, Corresponding-Image, valid) then
269:         if Corrupt[Identity]="Active" & valid=0 then
270:             UpdateBuffer({Receiver,"Create Node Get Image continue", session-id, user-id,
image-id, Node-Structure, Corresponding-Image, valid}, {Receiver,"Create Node result con-
tinue", session-id, user-id, image-id, Node-Structure, Fail});
271:              $C_3ID_{10}$ – Send-Env( $\mathcal{F}_{Compute}$ , Receiver, "Create Node", session-id, NULL,
Fail);%GOTO  $C_3ID_4^*$ 
272:         else if Corrupt[Identity]="Active" & valid=1 then
273:             UpdateBuffer({Receiver,"Create Node Get Image continue", session-id, user-id,
image-id, Node-Structure, Corresponding-Image, valid}, {Receiver,"Create Node get node ID",
session-id, user-id, image-id, Node-Structure, Corresponding-Image, valid});
274:              $C_3ID_{10}$ – Send-Env( $\mathcal{F}_{Compute}$ , Adversary, "Request Node ID", session-id);%GOTO
 $C_3ID_{11}$ 
275:         end if
276:     else if FindBuffer( $\mathcal{F}_{Compute}$ , destination, message) where the request-ID in the message is
equal to session-id then
277:         if destination= $\mathcal{F}_{Identity}$  then
278:             if Corrupt[Identity]!="Active" then
279:                 if FindDBRequest(session-id, Credential, ServiceObject-List, Black-List) where
request-ID=session-id & Credential=creds & ( $\mathcal{F}_{Compute}$ ,Object)  $\in$  ServiceObject-List &
 $\mathcal{F}_{Compute} \notin$  Black-List then
280:                     AddBlack-Listsession-id( $\mathcal{F}_{Compute}$ );
281:                     valid=successful;
282:                 else
283:                     valid=fail;
284:                 end if
285:                 UpdateBuffer({ $\mathcal{F}_{Compute}$ , destination, message}, {Receiver=destination,
Sender=  $\mathcal{F}_{Compute}$ , "Service validated", session-id, Request, valid});
286:                  $C_3C_1ID_1$ – Send-Env(Receiver, Sender, "Service validated", Request, valid); %
GOTO  $C_3C_1ID_2$ 
287:             else
288:                 Send-Env( $\mathcal{F}_{Compute}$ , Adversary, message);% adversary can either forward a mes-
sage or make a create/delete node request.
289:             end if
290:         else if destination= $\mathcal{F}_{Image}$  then
291:             if Corrupt[Image]!="Active" then
292:                 if FindDBRequest(session-id, Credential, ServiceObject-List, Black-List) where
request-ID=session-id & Credential=creds & ( $\mathcal{F}_{Image}$ ,image-id)  $\in$  ServiceObject-List &  $\mathcal{F}_{Image}$ 
 $\notin$  Black-List then
293:                     extract user-id from the message;
294:                     Message= message that the user credential is replaced by user-id;
295:                     UpdateBuffer({ $\mathcal{F}_{Compute}$ , destination, message},{ "Result",  $\mathcal{F}_{Compute}$ , destina-
tion, message});

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296:          $C_3C_1I_1$ – Send-IdealCloud(Message); %GOTO  $C_3C_1I_2$ 
297:         else
298:             UpdateBuffer({ $\mathcal{F}_{Compute}$ , destination, message},{ $\mathcal{F}_{Image}$ ,  $\mathcal{F}_{Compute}$ , "Get Image", session-id, image-id, NULL, Fail});
299:              $C_3C_1I_1$ – Send-Env( $\mathcal{F}_{Image}$ ,  $\mathcal{F}_{Identity}$ , "Service Validation", session-id,  $\mathcal{F}_{Image}$ -id, user-id, "Get Image image-id ");%GOTO  $C_3C_1I_4$ 
300:         end if
301:         else
302:             Send-Env( $\mathcal{F}_{Compute}$ , Adversary, message);% adversary can either forward a message or make a create/delete node request.
303:         end if
304:     end if
305:     else if FindBuffer(Receiver, Sender, "Service validated", session-id, Request, valid) then
306:         if Sender= $\mathcal{F}_{Compute}$  & Corrupt[Compute]="Active" then
307:              $C_3C_1ID_2$ – Send-Env(Receiver, Adversary, message);
308:         else if Sender= $\mathcal{F}_{Image}$  & Corrupt[Image]="Active" then
309:              $C_3I_7ID_2$ – Send-Env(Receiver, Adversary, message);
310:         end if
311:     else if FindBuffer( $\mathcal{F}_{Image}$ , destination, message) where the session-ID in the message is equal to session-id then
312:         if destination=  $\mathcal{F}_{Compute}$  & message=("Image", session-id, image-id, Corresponding-Image ) & FindBuffer(Receiver, "Get Image Result", session-id, user-id, image-id, "Corrupted Get Image") where the message request-ID=session-id then
313:             UpdateBuffer({Receiver, "Get Image Result", session-id, user-id, image-id, "Corrupted Get Image"}, {Receiver, "Node ID", session-id, user-id, image-id, "Corrupted Get Image"}, Corresponding-Image});
314:             RemoveBuffer( $\mathcal{F}_{Image}$ , destination, message);
315:              $C_3I_7$ – Send-Env ( $\mathcal{F}_{Compute}$ , Adversary, "Request Node ID", session-id);
316:         else if destination= $\mathcal{F}_{Identity}$  then
317:             if Corrupt[Identity] !="Active" then
318:                 if FindDBRequest(session-id, Credential, ServiceObject-List, Black-List) where request-ID=session-id & Credential=creds & ( $\mathcal{F}_{Image}$ ,Object)  $\in$  ServiceObject-List &  $\mathcal{F}_{Image} \notin$  Black-List then
319:                     AddBlack-Listsession-id( $\mathcal{F}_{Image}$ );
320:                     valid=successful;
321:                 else
322:                     valid=fail;
323:                 end if
324:             StoreBuffer(Receiver=destination, Sender=  $\mathcal{F}_{Image}$ , "Service validated", session-id, Request, valid);
325:              $C_3I_7ID_1$ – Send-Env(Receiver, Sender, "Service validated", Request, valid);
326:         else
327:             Send-Env( $\mathcal{F}_{Image}$ , Adversary, message);
328:         end if
329:     end if

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330:   else if FindBuffer( $\mathcal{F}_{Image}$ ,  $\mathcal{F}_{Compute}$ , "Get Image", session-id, image-id, Corresponding-
      Image, valid") then
331:     AddBlack-Listsession-id( $\mathcal{F}_{Image}$ );
332:     UpdateBuffer( $\{\mathcal{F}_{Image}, \mathcal{F}_{Compute}, \text{"Get Image"}, \text{session-id}, \text{image-id}, \text{Corresponding-}$ 
      Image, valid $\}$ ,  $\{\mathcal{F}_{Image}, \mathcal{F}_{Compute}, \text{"validated Get Image"}, \text{session-id}, \text{image-id}, \text{Corresponding-}$ 
      Image, valid $\}$ );
333:      $C_3C_1I_4$ – Send-Env ( $\mathcal{F}_{Identity}, \mathcal{F}_{Image}$ , "Service Validated", session-id, user-id, service-id,
      Request="Get Image image-id ", valid);
334:     else if FindBuffer( $\mathcal{F}_{Image}, \mathcal{F}_{Compute}$ , "validated Get Image", session-id, image-id,
      Corresponding-Image, valid") then
335:       UpdateBuffer( $\{\mathcal{F}_{Image}, \mathcal{F}_{Compute}, \text{"validated Get Image"}, \text{session-id}, \text{image-id},$ 
      Corresponding-Image, valid $\}$ ,  $\{\mathcal{F}_{Image}, \mathcal{F}_{Compute}, \text{"Result Get Image"}, \text{session-id}, \text{image-id},$ 
      Corresponding-Image, valid $\}$ );
336:        $C_3C_1I_5$ – Send-Env( $\mathcal{F}_{Image}, \mathcal{F}_{Compute}$ , "Image", session-id, image-id, Corresponding-
      Image);
337:     else if FindBuffer( $\mathcal{F}_{Image}, \mathcal{F}_{Compute}$ , "Result Get Image", session-id, image-id,
      Corresponding-Image, valid") then
338:       RemoveBuffer( $\mathcal{F}_{Image}, \mathcal{F}_{Compute}$ , "Result Get Image", session-id, image-id,
      Corresponding-Image, valid");
339:       if Corrupt[Compute]="Active" then
340:          $C_3C_1I_6$ – Send-Env( $\mathcal{F}_{Compute}$ , Adversary, message);
341:       end if
342:     else if FindBuffer("Output", Service, destination, message) then
343:       RemoveBuffer("Output", Service, destination, message);
344:     if Service= $\mathcal{F}_{Compute}$  & Corrupt[Compute]="Active" & message contains "Delete Node"
      then
345:        $D_3O_1$ – Send-IdealCloud(Receiver, "Delete Node", session-id, node-id, valid);
346:     else if Service= $\mathcal{F}_{Compute}$  & Corrupt[Compute]="Active" & message contains "Create
      Node" then
347:        $C_3C_1O_1$ – Send-IdealCloud(Receiver, "Create Node result", session-id, node-id,
      valid);
348:     end if
349:     else if FindBuffer(Receiver, "Service Validation", session-id, user-id, image-id, "Corrupted
      Get Image") then
350:       AddBlack-Listsession-id( $\mathcal{F}_{Compute}$ );
351:       UpdateBuffer( $\{\text{Receiver}, \text{"Service Validation"}, \text{session-id}, \text{user-id}, \text{image-id}, \text{"Corrupted}$ 
      Get Image $\}$ ,  $\{\text{Receiver}, \text{"Service Validatied"}, \text{session-id}, \text{user-id}, \text{image-id}, \text{"Corrupted Get}$ 
      Image $\}$ )
352:        $C_3I_3$ – Send-Env( $\mathcal{F}_{Identity}, \mathcal{F}_{Compute}$ , "Service Validated", session-id, user-id, Compute-
      id, "Create Node", Successful);
353:     else if FindBuffer(Receiver, "Service Validatied", session-id, user-id, image-id, "Corrupted
      Get Image") then
354:       UpdateBuffer( $\{\text{Receiver}, \text{"Service Validatied"}, \text{session-id}, \text{user-id}, \text{image-id}, \text{"Corrupted}$ 
      Get Image $\}$ ,  $\{\text{Receiver}, \text{"Get Image"}, \text{session-id}, \text{user-id}, \text{image-id}, \text{"Corrupted Get Image"}\}$ )
355:        $C_3I_4$ – Send-Env( $\mathcal{F}_{Compute}, \mathcal{F}_{Image}$ , "Get Image", session-id, user-id, image-id);

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356:   else if FindBuffer(Receiver, "Get Image", session-id, user-id, image-id, "Corrupted Get
Image") then
357:     UpdateBuffer({Receiver, "Get Image", session-id, user-id, image-id, "Corrupted Get
Image"}, {Receiver, "Get Image Result", session-id, user-id, image-id, "Corrupted Get Im-
age"});
358:     if Corrupt[Image]="Active" then
359:       if FindDBRequest(session-id, Request-Message, Credential, ServiceObject-List,
Black-List, Corruption) & Corruption ="Corrupt" then
360:         creds =Credential, ServiceObject-List;
361:       else
362:         Credential= Generate credential for the user;
363:         creds = Credential, ServiceObject-List;
364:         UpdateDBRequest for session-id with the new credential value and set Corrup-
tion="Corrupt";
365:       end if
366:        $C_3I_5$ – Send-Env( $\mathcal{F}_{Image}$ , Adversary, message = ("Get Image", session-id, creds,
image-id));% GOTO  $C_3I_6$  FOR FORWARDING,  $C_3I_6^*$  FOR MAKEING NEW REQUEST
367:       end if
368:       else if FindBuffer(Receiver, "Create Node Output", session-id) then
369:         RemoveBuffer(Receiver, "Create Node Output", session-id);
370:          $C_3I_{11}$ – Send-IdealCloud("Create Node Output", session-id);
371:
372:       else if FindBuffer(Receiver, "Delete Node Completed", session-id, user-id, node-id, valid,
NodeExist) then
373:          $D_3ID_6$ – Send-IdealCloud(Receiver, "Delete Node", session-id, node-id, valid);%GOTO
 $D_3O_2$ 
374:       else if FindBuffer(Receiver,"Delete Node", session-id, user-id, node-id) then
375:         if Corrupt[Compute]="Active" then
376:           if FindDBRequest(session-id, Request-Message, Credential, ServiceObject-List,
Black-List, Corruption) & Corruption ="Corrupt" then
377:             creds =Credential, ServiceObject-List;
378:           else
379:             Credential= Generate credential for the user;
380:             creds = Credential, ServiceObject-List;
381:             UpdateDBRequest for session-id with the new credential value and set Corrup-
tion="Corrupt";
382:           end if
383:            $D_3C$ – Send-Env(Receiver, Adversary, "Delete Node", session-id, node-id, creds);
384:           else if Corrupt[Identity]="Active" then
385:             UpdateBuffer({Receiver,"Delete Node", session-id, user-id, node-id },
{Receiver,"Corrupt Validation Delete Node", session-id, user-id, node-id });
386:              $D_3ID$ – Send-Env( $\mathcal{F}_{Compute}$ ,  $\mathcal{F}_{Identity}$ , "Service Validation", session-id, Compute-id,
user-id, "Delete Node");
387:           else
388:              $D_3$ – Send-IdealCloud("Confirm", session-id);
389:           end if

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390:   else if FindBuffer(Receiver,"Corrupt Validation Delete Node", session-id, user-id, node-id)
      then
391:       if Corrupt[Identity]="Active" then
392:           if FindDBRequest(session-id, Request-Message, Credential, ServiceObject-List,
      Black-List, Corruption) & Corruption ="Corrupt" then
393:               creds =Credential, ServiceObject-List;
394:           else
395:               Credential= Generate credential for the user;
396:               creds = Credential, ServiceObject-List;
397:               UpdateDBRequest for session-id with the new credential value and set Corrup-
      tion="Corrupt";
398:           end if
399:           Extract  $creds_{service}$  from ServiceCorrupt(Service, Service-id,  $creds_{service}$ ) where
      Service= $\mathcal{F}_{Compute}$ ;
400:           UpdateBuffer({Receiver,"Corrupt Validation Delete Node", session-id, user-id,
      node-id }, {Receiver,"Corrupt Validated Delete Node", session-id, user-id, node-id });
401:            $D_3ID_1$ – Send-Env(Receiver, Adversary, "Service Validation", session-id,
       $creds_{service}$ , creds);
402:           end if
403:       else if FindBuffer(Receiver,"Corrupt Result Delete Node", session-id, user-id, node-id,
      valid) then
404:           if Corrupt[Identity]="Active" then
405:               if valid=0 then
406:                   UpdateBuffer({Receiver,"Corrupt Result Delete Node", session-id, user-id, node-
      id, valid}, {Receiver,"Corrupt Output Delete Node", session-id, user-id, node-id, valid});
407:                    $D_3ID_3$ – Send-Env( $\mathcal{F}_{Compute}$ , Receiver, "Delete Node", session-id, node-id,
      Fail);%GOTO  $D_3ID_4^*$ 
408:               else
409:                   RemoveBuffer(Receiver,"Corrupt Result Delete Node", session-id, user-id, node-
      id, valid);
410:                    $D_3ID_3$ – Send-IdealCloud("Delete Node", session-id, node-id, valid); %GOTO
       $D_3ID_4$ 
411:               end if
412:           end if
413:       else if FindBuffer(Receiver,"Corrupt Output Delete Node", session-id, user-id, node-id,
      valid) then
414:            $D_3ID_4^*$ – Send-IdealCloud(Receiver,"Delete Node", session-id, node-id, valid);%GOTO
       $D_3O_2$ 
415:       else if FindBuffer(Receiver, "Node Access", session-id, user-id, node-id, RequestActivity)
      then
416:           Send-IdealCloud("Result Access Node", session-id)
417:       else if FindBuffer(Receiver, "Node Access", session-id, user-id, node-id, result, valid) then
418:           Send-IdealCloud("Output Access Node", session-id)
419:       else if FindBuffer(Receiver, "Attach Volume", session-id, volume-id, node-id) then
420:           if Identity is Corrupt then
421:               valid = validity setting used by simulated adversary

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422:     else
423:         valid=False
424:     end if
425:     Send-IdealCloud("Confirm Attach Volume", session-id, valid);
426: else if FindBuffer("Attach Volume", session-id, volume-id, node-id, valid) then
427:     Send-IdealCloud("Result Attach Volume", session-id)
428: else if FindBuffer("Attach Volume", session-id, volume-id, node-id, success/fail) then
429:     Send-IdealCloud("Output Attach Volume", session-id)
430: else if FindBuffer(Receiver, "Detach Volume", session-id, volume-id, node-id) then
431:     if Identity is Corrupt then
432:         valid = validity setting used by simulated adversary
433:     else
434:         valid=False
435:     end if
436:     Send-IdealCloud("Confirm Detach Volume", session-id, valid)
437: else if FindBuffer("Detach Volume", session-id, volume-id, node-id, valid) then
438:     Send-IdealCloud("Result Detach Volume", session-id)
439: else if FindBuffer("Detach Volume", session-id, volume-id, node-id, success/fail) then
440:     Send-IdealCloud("Output Detach Volume", session-id);
441: else if FindBuffer(Receiver, "Delete Service Validation", session-id, Service-id, user-id,
node-id, valid) then
442:      $D_6$ – Send-Env ( $\mathcal{F}_{Identity}$ ,  $\mathcal{F}_{Compute}$ , "Service Validated", session-id, user-id, service-id,
Request, valid);
443: else if FindBuffer(Receiver, "Delete Service Validated", session-id, user-id, node-id, valid)
then
444:     UpdateBuffer({Receiver, "Delete Service Validated", session-id, user-id, node-id,
valid},{Receiver, "Delete Node Continue", session-id, user-id, node-id, valid});
445:      $D_7$ – Send-IdealCloud ("Delete Node Output", session-id, continue);
446: else if FindBuffer(Receiver, "Output Delete Node", session-id) then
447:      $D_{10}$ – Send-IdealCloud("Output Delete Node", session-id);
448: else if FindBuffer(Receiver, "Service Validation", session-id, user-id, image-id, "Create
Node", create-valid, "Get Image", Image-valid, Corresponding-Image) then
449:     UpdateBuffer({Receiver, "Service Validation", session-id, user-id, image-id, "Create
Node", create-valid, "Get Image", Image-valid, Corresponding-Image},{Receiver, "Service Val-
idated", session-id, user-id, image-id, Service-id, "Create Node", create-valid, "Get Image",
Image-valid, Corresponding-Image})
450:     Add Black-Listsession-id( $\mathcal{F}_{Compute}$ );
451:      $C_6$ – Send-Env( $\mathcal{F}_{Identity}$ ,  $\mathcal{F}_{Compute}$ , "Service Validated", session-id, user-id, Compute-id,
"Create Node", create-valid);
452: else if FindBuffer(Receiver, "Service Validated", session-id, user-id, image-id, Compute-id,
"Create Node", create-valid, "Get Image", Image-valid, Corresponding-Image) then
453:     if create-valid=successful then

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454:      UpdateBuffer({Receiver, "Service Validated", session-id, user-id, image-id,
      Compute-id, "Create Node", create-valid, "Get Image", Image-valid, Corresponding-
      Image},{Receiver, "Get Image Create Node", session-id, user-id, image-id, Compute-id, Image-
      valid, Corresponding-Image})
455:       $C_7I, C_7II$ – Send-Env ( $\mathcal{F}_{Compute}, \mathcal{F}_{Image}$ , "Get Image", session-id, user-id, image-id,
      ServiceObject-List);
456:      else
457:      UpdateBuffer({Receiver, "Service Validated", session-id, user-id, image-id,
      Compute-id, "Create Node", create-valid, "Get Image", Image-valid, Corresponding-
      Image},{Receiver, "Create Node Output", session-id });
458:       $C_7III$ – Send-Env( $\mathcal{F}_{Compute}, Receiver$ , "Node Created", session-id, NULL, Fail);
459:      end if
460:      else if FindBuffer(Receiver, "Get Image Create Node", session-id, user-id, image-id,
      Compute-id, Image-valid, Corresponding-Image) then
461:      UpdateBuffer({Receiver, "Get Image Create Node", session-id, user-id, image-id,
      Compute-id, Image-valid, Corresponding-Image},{Receiver, "Get Image Service Validation",
      session-id, image-id, FImage-id, Image-valid, Corresponding-Image});
462:       $C_8I, C_8II$ – Send-Env( $\mathcal{F}_{Image}, \mathcal{F}_{Identity}$ , "Service Validation", session-id, FImage-id,
      user-id, "Get Image Image-id", ServiceObject-List);
463:      else if FindBuffer(Receiver, "Get Image Service Validation", session-id, image-id, FImage-
      id, Image-valid, Corresponding-Image) then
464:      UpdateBuffer({Receiver, "Get Image Service Validation", session-id, user-id, image-id,
      Compute-id, Image-valid, Corresponding-Image},{Receiver, "Get Image Service Validated",
      session-id, image-id, FImage-id, Image-valid, Corresponding-Image})
465:      Add Black-Listsession-id( $\mathcal{F}_{Image}$ );
466:       $C_9I, C_9II$ – Send-Env( $\mathcal{F}_{Identity}, \mathcal{F}_{Image}$ , "Service Validated", session-id, user-id, Fimage-
      id, "Get Image image-id", Image-valid, ServiceObject-List);
467:      else if FindBuffer(Receiver, "Get Image Service Validated", session-id, image-id, FImage-
      id, Image-valid, Corresponding-Image) then
468:      if Image-valid =false then
469:      Corresponding-Image=NULL
470:      end if
471:      UpdateBuffer({Receiver, "Get Image Service Validated", session-id, image-id, FImage-
      id, Image-valid, Corresponding-Image},{Receiver, "Get Image Continue", session-id, image-id,
      Image-valid, Corresponding-Image})
472:       $C_{10}I, C_{10}II$ – Send-Env( $\mathcal{F}_{Image}, \mathcal{F}_{Compute}$ , "Image", session-id, image-id,
      Corresponding-Image);
473:

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474:   else if FindBuffer(Receiver, "Get Image Continue", session-id, image-id, Image-valid,
Corresponding-Image) then
475:       if Corresponding-Image=NULL then
476:           UpdateBuffer({Receiver, "Get Image Continue", session-id, image-id, Image-valid,
Corresponding-Imaged},{Receiver, "Create Node Output", session-id })
477:            $C_{11II}$ – Send-Env ( $\mathcal{F}_{Compute}$ , Receiver, "Node Created", session-id, NULL, Fail);
478:       else
479:           UpdateBuffer({Receiver, "Get Image Continue", session-id, image-id, Image-valid,
Corresponding-Imaged},{Receiver, "Request NodeID", session-id })
480:
481:            $C_{11I}$ – Send-Env( $\mathcal{F}_{Compute}$ , Adversary, "Request Node ID", session-id);
482:       end if
483:
484:   else if FindBuffer(Receiver, "Create Node Output", session-id) then
485:       RemoveBuffer (Receiver, "Create Node Output", session-id);
486:        $C_{8III}, C_{12II}, C_{15I}$ – Send-IdealCloud ("Create Node Output", session-id);
487:
488:   end if
489:
490:    $D_5$ – Upon receiving (Receiver, "Delete Node", session-id, user-id, node-id, valid) from
Ideal Cloud:
491:   Service-id=Service-id for  $F_{Compute}$ 
492:   UpdateBuffer({Receiver,"Delete Node", session-id, user-id, node-id }, {Receiver, "Delete
Service Validation", session-id, Service-id, user-id, node-id, valid});
493:   Send-Env( $\mathcal{F}_{Compute}, \mathcal{F}_{Identity}$ , "Service Validation", session-id, Compute-id, user-id, "Delete
node-id ");
494:
495:    $D_9$ – Upon receiving( "Delete Node Completed", session-id, Valid, NodeExist) from Ideal-
Cloud:
496:   if FindBuffer(Receiver, "Delete Node Continue", session-id, user-id, node-id, valid) then
497:       UpdateBuffer ( {"Delete Node Continue", session-id, user-id, node-id, valid}, {"Output
Delete Node", session-id })
498:       if NodeExist=0 or Valid=0 then
499:           Send-Env ( $\mathcal{F}_{Compute}$ , Receiver, "Delete Node", session-id, node-id, Fail);
500:       else
501:           Send-Env ( $\mathcal{F}_{Compute}$ , Receiver, "Delete Node", session-id, node-id, Successful);
502:       end if
503:   end if

```

```

504:    $C_5I$ – Upon receiving (Receiver, "Get Node ID", session-id, user-id, image-id, Node-
      Structure, Corresponding-Image) from Ideal Cloud:
505:   StoreBuffer(Receiver, "Service Validation", session-id, user-id, image-id, "Create Node",
      Successful, "Get Image", Successful, Corresponding-Image);
506:   Send-Env( $\mathcal{F}_{Compute}$ ,  $\mathcal{F}_{Identity}$ , "Service Validation", session-id, Compute-id, user-id, "Create
      Node Node-Structure with ServiceObject-List ");% GOTO  $C_6$ 
507:
508:    $C_5II$ – Upon receiving (Receiver, "Create Node", session-id, user-id, Fail, reason="Get
      Image", Node-Structure) from Ideal Cloud:
509:   StoreBuffer(Receiver, "Service Validation", session-id, user-id, "Create Node", Successful,
      "Get Image", Fail, NULL);
510:   Send-Env( $\mathcal{F}_{Compute}$ ,  $\mathcal{F}_{Identity}$ , "Service Validation", session-id, Compute-id, user-id, "Create
      Node Node-Structure with ServiceObject-List ");% GOTO  $C_6$ 
511:
512:    $C_5III$ – Upon receiving (Receiver, "Create Node", session-id, user-id, Fail, reason="Create
      Node", Node-Structure) from Ideal Cloud:
513:   StoreBuffer(Receiver, "Service Validation", session-id, user-id, "Create Node", Fail, "Get
      Image", Fail, NULL);
514:   Send-Env( $\mathcal{F}_{Compute}$ ,  $\mathcal{F}_{Identity}$ , "Service Validation", session-id, Compute-id, user-id, "Create
      Node Node-Structure with ServiceObject-List ");% GOTO  $C_6$ 
515:
516:    $C_{14}I$ – Upon receiving ("Create Node Continue", session-id, user-id, valid) from IdealCloud:
517:   if FindBuffer(Receiver, "Node ID continue", session-id, node-id) then
518:     UpdateBuffer({Receiver, "Node ID continue", session-id },{Receiver, "Create Node
      Output", session-id })
519:     Send-Env ( $\mathcal{F}_{Compute}$ , Receiver, "Node Created", session-id, node-id, valid);
520:   end if
521: end function

```

the same service. To realize these properties, the simulator no longer store credentials per user-id; instead, it creates and stores one credential per each compromised session-id.

That is, when Nova is compromised, the simulator notifies the ideal cloud and the ideal cloud sends all session-id in which the requests are either new to Nova or not finalized. Next, the simulator creates credentials for each session-id, stores them together with the request detail (scope) in its database for future use, and adds these credentials to the corresponding messages as needed. In addition, because of second property, the simulator creates a blacklist for each session-id and adds the services which have made a request for validation. In this way, the simulator is able to track all service requests for validation and properly respond to the requests such that E views identical messages from both worlds.

When an adversary uses a compromised session-id =5 with request detail of “CreateNode with image-id =2” and makes a GetImage request to Glance for image-id =2, the Glance needs to validate the credential first then send the corresponding image. For this case, the simulator creates all the intermediate messages until it reaches the validation result message to Glance. If Glance has previously made a request with same credential for session-id =5, then the simulator will send a failed result (because this service is in the blacklist of session-id =5 in the simulator). If the credential is correct, then S first adds Glance to the blacklist of session-id =5 and then S sends the successful result. This means that if the specification of the corresponding image related to image-id =2 changes in the future, then the adversary *cannot* access the more recent and up to date information which is what happens in the OpenStack Services.

Note that even though getting access to the most recent image specification may not be a great interest for the adversary, but the point here is that the adversary cannot get the updates for any other request in which the update information is crucial.

On the hand, because of one-time token’s scope property, the simulator stores the request detail and does not permit a request with different scope for the same session-id. That is (in our example), if the adversary makes a request of accessing corresponding image of image-id =7 for session-id =5, then the simulator will send a fail result (because the scope of this request is ”create a node with image-id =2 for session-id =5”).

6.4.2 Property 4: Cryptographic design ensures one time use

In this section, we demonstrate that the Recursive Augmented Fernet Token (RAFT) described in Algorithm 28 suffices to ensure one-time use. Because the construction involves cryptography, this is the only part of the proof in which simulation only holds against computationally-bound adversaries.

The strength of RAFT boils down to the intersection of three properties:

1. The cryptographic strength of HMAC, which is unforgeable by any computationally-constrained adversary who does not possess the key.
2. The method by which keys are doled out by Keystone, and then recursively by users to services, to ensure that the HMAC can only be performed by authorized services.
3. $\mathcal{F}_{Identity}$ ’s validation algorithm, which sends an alert to an (uncompromised) service if any of the following hold: the token is reused, the HMAC is invalid, or a service produces an HMAC for a request that isn’t within the authorized scope of a prior request in the chain.

We apply the three properties in sequence to realize the scoped and single-use properties of RAFT. First, by a standard hybrid argument it suffices to replace the pseudorandom HMAC with a truly random function. Via a reasoning up-to-bad argument, we may safely condition the remainder of our argument on the (overwhelming) likelihood that a forgery doesn't occur, in which case our invariant is maintained that E 's view is unchanged. The second property demonstrates that if forgeries do not occur, then the recursive tokens form a chain of requests that ultimately tie back to a single authorization made by the user. Finally, the third property demonstrates both that the token can only be used once and also that the token preserves scope; more specifically, the tokens in the chain 'link' together in the sense that the request made by each service must be a logical consequence of the request made by a prior service.

7 Conclusion & Future Work

This work lays the foundation for a full-scope composable security analysis for the popular cloud management framework OpenStack. We believe that this effort can bring communities together. On the one hand, our abstract model is substantially easier to absorb than the code of OpenStack and therefore opens OpenStack to a wider group within the cryptography and programming languages communities. On the other hand, our modular analysis provides the OpenStack development community with a better understanding of the security concerns surrounding some of its core design issues as well as (more importantly) a concise, tangible description of how the security of the overall cloud concretely improves by making moderate software improvements. Put differently: the modular analysis can both expose bugs and provide motivation for the developers to address them.

Even so, this work covers only some of the core functionality provided by a full featured cloud. In particular, there are still many remaining features necessary for fine grained access control. Much more work is needed in order to: (a) cover more services, (b) consider more attack (corruption) options and the security guarantees provided in these cases, and (c) analyze implementations of the various services and the associated security caveats and vulnerabilities. The last point is where the power of universal composability is put to use: our model can be extended to include internal components of services such as Compute and Storage in order to show how these subsystems combine to realize the ideal services $\mathcal{F}_{Compute}$ and $\mathcal{F}_{BlockStorage}$ that we use in this work. This level of modeling also enables clearer discussion of the effects of single-node compromises.

Another natural direction for future research is mechanizing the analysis, and in particular the proofs of security, such as the one done here. Indeed, we are already taking first steps toward formalizing UC security within the EasyCrypt computer-aided proof system.

We believe that this work provides an important benchmark to show the feasibility of modeling large-scale software packages within the framework of Universal Composability. Modularity was a crucial component toward keeping the models and analyses manageable. Indeed, this work demonstrates the value of conducting similar analyses of other software deployments in the future.

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A Notations Description

Table 1 provides a brief description of notions used in algorithms 8, 26, 29, and 32. Figures 4 and 5 represent the message flow between the ideal cloud IC , simulator S , and environment E represented in these algorithms. These information aim in guiding readers to understand the algorithms easier.

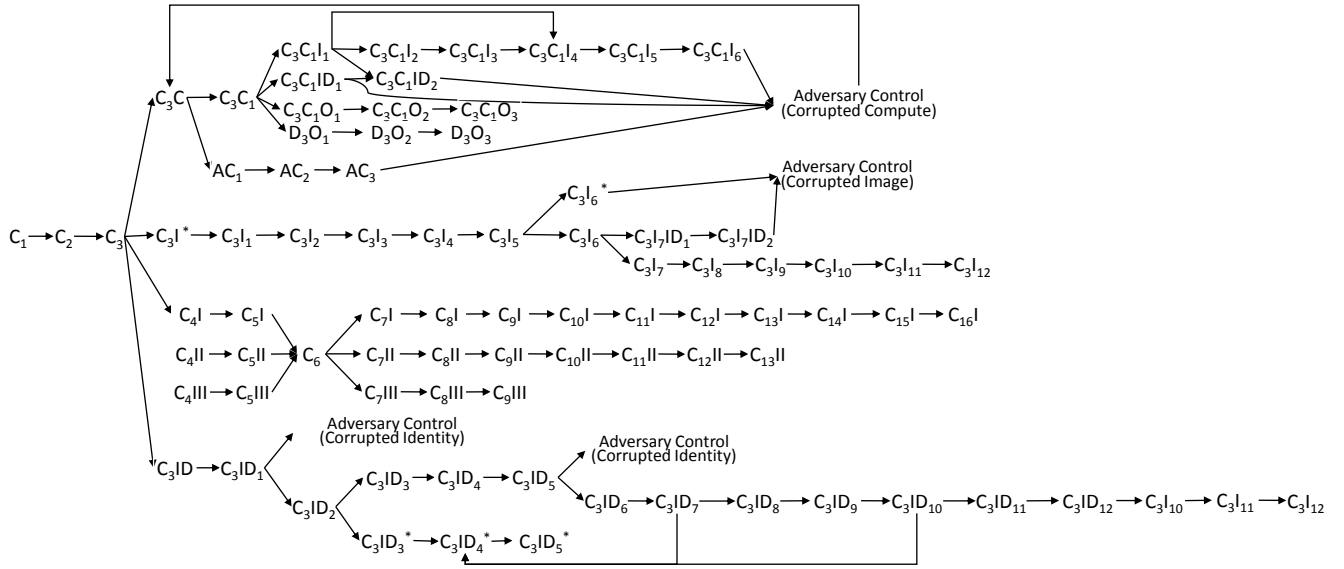


Figure 4: Create Node flowchart which shows the interaction between the ideal cloud, simulator, and environment E . This flowchart is valid for both one-time token and bearer token mechanisms. Table 1 describes the notation used in this flowchart.

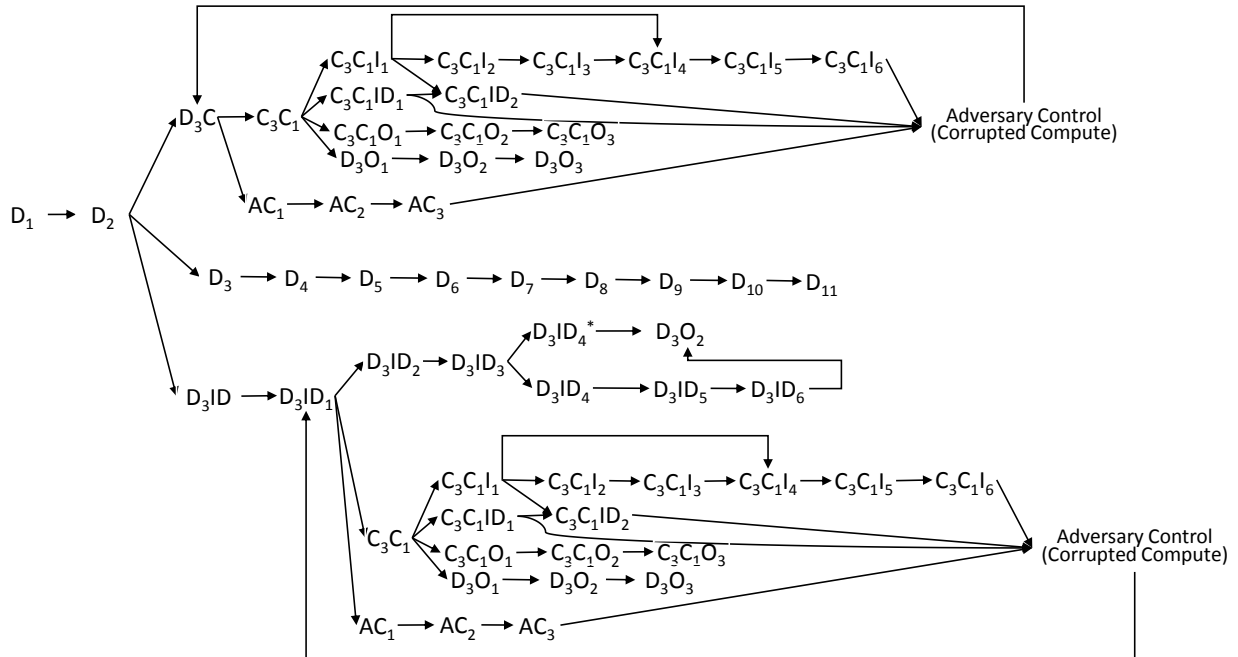


Figure 5: Delete Node flowchart which shows the interaction between the ideal cloud, simulator, and environment E . This flowchart is valid for both one-time token and bearer token mechanisms. Table 1 describes the notation used in this flowchart.

Table 1: notation description

| | |
|--------------|---|
| C_1 | Create node request from user. (IC) |
| C_2 | S sends the create node request to E and waits for the confirmation. (S) |
| C_3 | Request: Create node, Situation: no corruption By receiving confirmation message from E , S sends a confirmation message to IC . (S) |
| C_3C | Request: Create node, Situation: corrupted Compute S creates a unique credential for the user (if it has not been created before) and together with the message sends it to A and gives the control to A . (S) |
| C_3C_1 | Request: Anything, Situation: corrupted Compute A has made a forward request. Thus, S sends it to E and waits for the confirmation. (S) |
| $C_3C_1I_1$ | Request: Create node, Situation: corrupted Compute, uncorrupted Image A has made a forward request. The request is to get the corresponding image to image-id. When Image is not corrupted, S sends the request to the ideal cloud to get the result, if the user is allowed to make such request (in one-time token mechanism) otherwise, sends the validation request to E . (S) |
| $C_3C_1I_2$ | Request: Create node, Situation: corrupted Compute, uncorrupted Image If Compute is corrupted while Image service is not corrupted and A makes an Image request. Ideal cloud sends back the result S . (IC) |
| $C_3C_1I_3$ | Request: Create node, Situation: corrupted Compute, uncorrupted Image S receives corresponding image to image-id from the ideal cloud. It sends the validation request and waits for confirmation. (S) |
| $C_3C_1I_4$ | Request: Create node, Situation: corrupted Compute, uncorrupted Image After receiving confirmation, the result of the validation is provided to E and waits for confirmation. (S) |
| $C_3C_1I_5$ | Request: Create node, Situation: corrupted Compute, uncorrupted Image After receiving confirmation from E , S sends the corresponding-Image of image-id to E . And finally after E confirms, the corresponding-Image result will be given to A (for the corrupted Compute). (S) |
| $C_3C_1I_6$ | Request: Create node, Situation: corrupted Compute, uncorrupted Image After receiving confirmation from E , S sends the corresponding-Image of image-id to A . (S) |
| $C_3C_1ID_1$ | Request: validation, Situation: corrupted Compute A has made a forward request. The request is to validate a request. If Identity is not corrupted, S sees in the DB if this request is compromised and give correct answer, while if the Identity is also corrupted, sends the message to A . (S) |
| $C_3C_1ID_2$ | Request: validation, Situation: corrupted Compute, uncorrupted Identity S sends the validation result to A . (S) |
| $C_3C_1O_1$ | Request: Output create node result, Situation: corrupted Compute A has made a forward request to show its output to the user. Thus S sends the output result to E and wait for confirmation. (S) |
| $C_3C_1O_2$ | Request: Output create node result, Situation: corrupted Compute After receiving confirmation from E , S sends the output result to the ideal cloud. (S) |
| $C_3C_1O_3$ | Request: Output create node result, Situation: corrupted Compute IC outputs whatever A wants to the user. (IC) |
| C_3I^* | Request: create node, Situation: corrupted Image S sends a message to IC to get more information. (S) |
| C_3I_1 | Request: create node, Situation: corrupted Image The ideal cloud needs to get the corresponding-Image from A if the user is able to create a node. It sends message to S . (IC) |
| C_3I_2 | Request: create node, Situation: corrupted Image |

| | |
|--------------|--|
| | <i>S</i> sends validation request to <i>E</i> and wait for confirmation. (<i>S</i>) |
| C_3I_3 | Request: create node, Situation: corrupted Image By receiving confirmation for <i>E</i> , <i>S</i> creates validation result and send it to <i>E</i> and wait for confirmation. (<i>S</i>) |
| C_3I_4 | Request: create node, Situation: corrupted Image <i>S</i> create a message on behalf of Compute to the Image and request corresponding-Image for image-id and wait for confirmation. (<i>S</i>) |
| C_3I_5 | Request: create node, Situation: corrupted Image <i>S</i> sends the message the is received by Image to <i>A</i> . (<i>S</i>) |
| C_3I_6 | Request: anything, Situation: corrupted Image <i>A</i> sends a message on behalf of Image. (<i>S</i>) |
| $C_3I_6^*$ | Request: anything, Situation: corrupted Image <i>A</i> makes a Get Image request when Image is corrupted. <i>S</i> sends back the result. (<i>S</i>) |
| C_3I_7 | Request: create node, Situation: corrupted Image If <i>A</i> has created a message for compute with the image related to image-id (in the previous step), <i>S</i> sends a request to <i>E</i> to get node-id and wait for confirmation. (<i>S</i>) |
| $C_3I_7ID_1$ | Request: anything, Situation: corrupted Image\uncorrupted Identity <i>S</i> looks in the DB if this request and creates the proper message, sends to <i>E</i> and waits for confirmation. (<i>S</i>) |
| $C_3I_7ID_2$ | Request: anything, Situation: corrupted Image\corrupted Image <i>S</i> sends the messages to <i>A</i> . (<i>S</i>) |
| C_3I_8 | Request: create node, Situation: corrupted Image By receiving the node-id, <i>S</i> sends the information to <i>IC</i> so it can create the node. (<i>S</i>) |
| C_3I_9 | Request: create node, Situation: corrupted Image <i>IC</i> creates the node using the corresponding-image and image-id that <i>S</i> provided (if the node-id has not been used before) and sends the result to <i>S</i> . (<i>IC</i>) |
| C_3I_{10} | Request: create node, Situation: corrupted Image or corrupted identity By receiving the result of create node functionality, <i>S</i> provides the output to <i>E</i> and waits for the Confirmation. (<i>S</i>) |
| C_3I_{11} | Request: create node, Situation: corrupted Image or corrupted identity Sends a continue message to the ideal cloud to output the create node result to the user. (<i>S</i>) |
| C_3I_{12} | Request: create node, Situation: corrupted Image or corrupted identity <i>IC</i> outputs the result to the user. (<i>IC</i>) |
| C_3ID | Request: create node\delete node\access node, Situation: corrupted Identity <i>S</i> creates the validation message to Identity on behalf of Compute and waits for <i>E</i> confirmation. (<i>S</i>) |
| C_3ID_1 | Request: create node\delete node\access node, Situation: corrupted Identity <i>S</i> sends he result of validation to <i>A</i> . (<i>S</i>) |
| C_3ID_2 | Request: create node, Situation: corrupted Identity For situation which <i>A</i> decides to respond to a validation request made from Compute for create node. <i>S</i> sends the validation result to <i>E</i> . (<i>S</i>) |
| C_3ID_3 | Request: create node, Situation: corrupted Identity After <i>E</i> confirms the validation result message if result is successful, <i>S</i> creates a message for Image, to get the corresponding image for image-id. (<i>S</i>) |
| $C_3ID_3^*$ | Request: create node, Situation: corrupted Identity After <i>E</i> confirms the validation result message if result is fail, <i>S</i> creates output message on behalf of Compute and sends it to <i>E</i> . (<i>S</i>) |
| C_3ID_4 | Request: create node, Situation: corrupted Identity <i>S</i> creates message on behalf of Image to Identity to get validation result and wait for <i>E</i> confirmation. (<i>S</i>) |

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| $C_3ID_4^*$ | Request: create node, Situation: corrupted Identity S sends a message to IC to output the fail result. (S) |
| C_3ID_5 | Request: create node, Situation: corrupted Identity S sends validation message on behalf of Image for create node request. This message is sent to A . (S) |
| $C_3ID_5^*$ | Request: create node, Situation: corrupted Identity IC outputs the create node result that was provided by S to the user. (IC) |
| C_3ID_6 | Request: create node, Situation: corrupted Identity For situation which A decides to respond to a request made from Image Service. S sends the validation result to E and waits for confirmation. (S) |
| C_3ID_7 | Request: create node, Situation: corrupted Identity By receiving the confirmation from E if the Get Image is valid then S sends a message to IC to create the node. If the request is invalid, it creates the output and waits for E confirmation. (S) |
| C_3ID_8 | Request: create node, Situation: corrupted Identity IC sends the corresponding-Image to S . (IC) |
| C_3ID_9 | Request: create node, Situation: corrupted Identity S receive leaks corresponding image to E and wait for confirmation. (S) |
| C_3ID_{10} | Request: create node, Situation: corrupted Identity By receiving confirmation from E , S sends a message to get node-id from A . (S) |
| C_3ID_{11} | Request: create node, Situation: corrupted Identity By receiving node-id from A , S sends this information to IC . (S) |
| C_3ID_{12} | Request: create node, Situation: corrupted Identity IC creates the node and provides the result to S . (IC) |
| C_4I, C_4II C_4III | Request: create node, Situation: no corruption IC sends the result of validation and related information for create node to S . I: when the user is allowed to create a node and allowed to use image-id. II: when the user is allowed to create a node but not allowed to use image-id. III: when the user is not allowed to create a node. (IC) |
| $C_5I, C_5II,$ C_5III | Request: create node, Situation: no corruption By receiving information regarding create node validation, S creates a validation request message on behalf of compute to Identity and sends it to E . (S) |
| C_6 | Request: create node, Situation: no corruption By receiving confirmation message from E , S sends the validation result and waits for confirmation. (S) |
| C_7I, C_7II | Request: create node, Situation: no corruption By receiving confirmation message from E , for I,II: S creates a message on behalf of Compute to Image to get image related to image-id, sends it to E and waits for confirmation. III: S sends the output message to E and waits for confirmation. (S) |
| C_8I, C_8II | Request: create node, Situation: no corruption By receiving confirmation message from E , S creates a validation request on behalf of Image to Identity, sends it to E and waits for confirmation. (S) |
| C_9I, C_9II | Request: create node, Situation: no corruption By receiving confirmation message from E , S creates a validation result on behalf of Identity to Image, sends it to E and waits for confirmation. (S) |
| C_{10I}, C_{10II} | Request: create node, Situation: no corruption By receiving confirmation message from E , for S creates a message on behalf of Image to Compute with corresponding image for image-id, sends it to E and waits for confirmation. (S) |
| C_{11I} | Request: create node, Situation: no corruption |

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| | By receiving confirmation message from E , S creates a message to request node-id from \mathcal{A} and sends it to E . (S) |
| C_{12I} | Request: create node, Situation: no corruption By receiving node-id from E , S sends node-id to IC . (S) |
| C_{13I} | Request: create node, Situation: no corruption By node-id from S , IC creates the node and sends the result to S . (IC) |
| $C_{14I}, C_{11II}, C_{7III}$ | Request: create node, Situation: no corruption I: By receiving result message from IC , S sends the output message to E and waits for confirmation. II, III: By receiving confirmation message from E , S sends the output message to E and waits for confirmation. (S) |
| $C_{15I}, C_{12II}, C_{8III}$ | Request: create node, Situation: no corruption By receiving confirmation message from E , S sends confirmation message to IC . (S) |
| $C_{16I}, C_{13II}, C_{9III}$ | Request: create node, Situation: no corruption By receiving confirmation message S , IC notifies the user about the request result. (IC) |
| AC_1 | Request: create node\delete node\access node, Situation: corrupted Compute \mathcal{A} makes a request on behalf of compute. S sends the request to the ideal cloud and waits for the result. (S) |
| AC_2 | Request: create node\delete node\access node, Situation: corrupted Compute The IC applies the request if it is possible (without checking validation) and sends the result to S (IC) |
| AC_3 | Request: create node\delete node\access node, Situation: corrupted Compute By receiving the result from IC , S notifies \mathcal{A} and gives the control to her. (S) |
| D_1 | Delete node request from user. The IC sends the request to S (IC) |
| D_2 | Request: Delete node, Situation: anything S leaks this message (without credentials) to E and waits for confirmation (S) |
| D_3 | Request: Delete node, Situation: no corruption By receiving confirmation from E , S sends a confirmation message to IC (S) |
| D_4 | Request: Delete node, Situation: no corruption IC validates the user and sends this information to S . (IC) |
| D_5 | Request: Delete node, Situation: no corruption By receiving information regarding validation from IC , S creates a validation request on behalf of Compute to Identity, sends it to E and waits for confirmation. (S) |
| D_6 | Request: Delete node, Situation: no corruption By receiving confirmation from E , S creates a validation response on behalf of Identity to Compute, sends it to E and waits for confirmation. (S) |
| D_7 | Request: Delete node, Situation: no corruption By receiving confirmation from E , S sends a confirmation message to IC . (S) |
| D_8 | Request: Delete node, Situation: no corruption IC checks if node exists and delete it and sends the result to S . (IC) |
| D_9 | Request: Delete node, Situation: no corruption S creates an output message, sends it to E and waits for confirmation. (IC) |
| D_{10} | Request: Delete node, Situation: no corruption By receiving confirmation from E , S sends a confirmation message to IC . (S) |
| D_{11} | Request: Delete node, Situation: no corruption IC outputs the result to the user. (IC) |
| D_3C | Request: Delete node, Situation: corrupted Compute S creates a unique credential for the user (if it has not been created before) and together with the message sends it to \mathcal{A} and gives the control to \mathcal{A} . (S) |
| D_3ID | Request: Delete node, Situation: corrupted Identity |

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| | <i>S</i> create the "Service Validation" message on behalf of Compute and sends it to <i>E</i> and waits for the Confirmation. (<i>S</i>) |
| D_3ID_1 | Request: Delete node, Situation: corrupted Identity <i>S</i> sends the message together with the credentials to <i>A</i> . (<i>S</i>) |
| D_3ID_2 | Request: Delete node, Situation: corrupted Identity If <i>A</i> decides to respond to a request made from Compute for delete node. <i>S</i> creates a message (with adversarial validation result) on behalf of Identity to Compute, sends it to <i>E</i> and waits for confirmation. (<i>S</i>) |
| D_3ID_3 | Request: Delete node, Situation: corrupted Identity By receiving the validation result from the corrupted Identity, <i>S</i> generates the fail result if the valid=fail for <i>E</i> and wait for confirmation. While if the valid=success, <i>S</i> sends this information to <i>IC</i> for the execution. (<i>S</i>) |
| D_3ID_4 | Request: Delete node, Situation: corrupted Identity The <i>IC</i> deletes the node if it is possible and notifies <i>S</i> . (<i>IC</i>) |
| D_3ID_5 | Request: Delete node, Situation: corrupted Identity <i>S</i> receives the result of deleting a node from <i>IC</i> , notifies <i>E</i> and waits for confirmation. (<i>S</i>) |
| D_3ID_6 | Request: Delete node, Situation: corrupted Identity By receiving confirmation message from <i>E</i> , <i>S</i> sends a continue message to <i>IC</i> . (<i>S</i>) |
| $D_3ID_4^*$ | Request: Delete node, Situation: corrupted Identity Sends to ideal cloud the result of the delete node. (<i>S</i>) |
| D_3O_1 | Request: Output delete node result, Situation: corrupted Compute <i>A</i> has made a forward request to show its output to the user. Thus <i>S</i> sends the output result to <i>E</i> and wait for confirmation. (<i>S</i>) |
| D_3O_2 | Request: Output delete node result, Situation: corrupted Compute After receiving confirmation from <i>E</i> , <i>S</i> sends the output result to the ideal cloud. (<i>S</i>) |
| D_3O_3 | Request: Output delete node result, Situation: corrupted Compute <i>IC</i> outputs whatever <i>A</i> wants to the user. (<i>IC</i>) |